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## Planetary Defense team project: READI (Roadmap for EArth Defense Initiatives)

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# PLANETARY DEFENSE

DETECTION

DEFLECTION

COLLABORATION

OUTREACH

EVACUATION

# READI

## ROADMAP FOR EARTH DEFENSE INITIATIVES

## FINAL REPORT





# **READI**

**ROADMAP FOR EARTH DEFENSE INITIATIVES**

**- A PLANETARY DEFENSE TEAM PROJECT -  
FINAL REPORT**

**INTERNATIONAL SPACE UNIVERSITY  
SPACE STUDIES PROGRAM 2015**

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Outreach Image - Dreamstime teacher with students in classroom

Evacuation Image - Libyan City of Syrte destroyed in 2011

Shield Image - Silver metal shield PNG image

The cover page was designed to include a visual representation of the roadmap for a robust Planetary Defense Program that includes five elements: detection, deflection, global collaboration, outreach, and evacuation. The shield represents the idea of defending our planet, giving confidence to the general public that the Planetary Defense elements are reliable. The orbit represents the comet threat and how it is handled by the shield, which represents the READI Project. The curved lines used in the background give a sense of flow representing the continuation and further development for Planetary Defense programs after this team project, as we would like for everyone to be involved and take action in this noble task of protecting Earth.

The 2015 Space Studies Program of the International Space University was hosted by the Ohio University, Athens, Ohio, USA.

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The ISU SSP15 Planetary Defense team wishes to express our sincere appreciation to NASA Science Mission Directorate and the Aerospace Corporation for their sponsorship of this project. Thanks also to the ISU SSP15 organizers for planning this team project, in which the 34 participants have become deeply involved over the past 9 weeks, creating new and durable friendships. Finally, we give our thanks to those who have read and will read our report based on their interest to contribute to the defense of our planet from cosmic threats. Preparation is the key to success and we can achieve this through the involvement of everyone from around the globe.

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# READI

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## Faculty Preface

In this Anthropocene era, where we have bestowed upon ourselves the title of “stewards of planet Earth”, in a world of many cutting-edge technologies, it is humbling to know that the power of nature still vastly exceeds all that we can bring to bear to prevent or avert natural upheavals and disasters.

For the first time in our evolution, as a progressive technology wielding species, space and other allied advanced technologies allow us to ameliorate the effects of some of these large scale calamities. We feel we are at the threshold of mastering the tools that will allow us to thwart asteroid and cometary impacts that play a critical role in shaping our planet and in the evolution of species. Transcending space situational awareness that allows us to monitor space weather routinely, an expanded solar system situational awareness is making us a more refined species, sensitive to changes more distant, where denizens of deep space like asteroids and comets lurk.

Far from just possibilities or imaginative conjectures, we continue to observe close encounters and study the effects of these impacts in our solar system neighborhood. The 2013 Chelyabinsk asteroid airburst that caused citywide damage and injury proved yet again that this natural phenomenon can disrupt lives and has to be dealt with. As our population grows, asteroids and comet impacts can cause untold misery for Earth’s flora and fauna alike, and depending on the energy release of the impact, the swift damage to physical infrastructure can be many times that of entire nuclear arsenals of the world’s greatest armies.

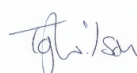
ISU SSP team projects have looked at NEOs and comets in the past. This latest edition is the third in the series after Cassandra in 2005 and Phoenix in 2007. The 2015 Planetary Defense team project: READI, looked at the potential for humanity as a whole to join forces to avert a cometary impact with a very short warning period, using current technologies and strategies. Employing a “more eyes on the skies” approach, and by crafting agile global networks for communications to execute a globally coordinated threat response, this truly international team from 17 countries, offers a unique global view of how to cooperate on this vital project to defend Earth from these hazardous deep space objects.

We expect that the following pages will shine some light on technologies and the infrastructures needed to build up sturdy planetary defense capabilities. We show how some existing but disparate organizations may be quilted to become effective as well as the strategic knowledge, technology and operational readiness gaps that need to be bridged, if we are to field a truly capable and reliable system to defend our home planet from asteroid and cometary impacts, and in the process engage an ever more tightly-knit world of nations in peaceful cooperation and collaboration.

Welcome to the READI Project and the tryst with comet Madhusa...



Madhu Thangavelu, Thomas Wilson, James Burke


## Participants' Preface

The READI Project is a product of the Planetary Defense team project, created during the Space Studies Program 2015 of the International Space University, which took place in Athens, Ohio from June 8 to August 7. Our team focused on a Planetary Defense strategy for a two-year warning period after the detection of a threat. This is what sets us apart from previous projects on near-Earth objects (NEOs) and long period comets (LPCs), and from current work on the subject. We have selected a comet for our scenario because they are an underrepresented topic in the literature regarding Planetary Defense, even though comets are far less predictable and would enter our atmosphere at faster velocities than asteroids, releasing more energy than asteroid impacts.

Most of the team members were not experts on the topic when the project began, with each member bringing their own field of expertise to the project and applying it to the problem. The complexity of the problem, both technically and socially, motivated us to participate in this project. We accepted the challenge and put forward our unique experiences to convey the problem, and to alert policy makers and the general public to take action on threats that can cause from city-level damage to global devastation. We did this with the use of five elements that we consider highly important and which cover critical angles of the issue. These include detection and tracking, deflection techniques, global collaboration, outreach and education, and evacuation and recovery. In addition, the seven departments of ISU were represented with dedicated liaisons, which helped us achieve the 3Is model of ISU: Interdisciplinary, International, and Intercultural.

This report is intended to educate the reader and put into perspective the need for action on Planetary Defense. Chapter 1 includes the background information about asteroids and comets, and emphasizes the importance of Planetary Defense. The rest of report is then divided in two main parts. Chapter 2 covers the current status of technologies and other activities for Planetary Defense, derived from literature review and visiting experts, as well as our proposed solutions and contingency plans. Chapter 3 is the application of our solutions to a comet threat scenario, looking at optimistic and pessimistic outcomes depending on the level of readiness reached beforehand within our roadmaps. This has been structured in a storytelling style to further engage the audience. Our recommendations are then compiled in Chapter 4, based on the elements that we proposed for the READI Project. We hope that you enjoy our report as much as we enjoyed putting it together. As authors of this report, our perspectives on how we view the world changed, knowing now how vulnerable we really are. The Planetary Defense team project is our small contribution to protecting our planet, and one we hope will inspire others.



## Abstract

Planetary Defense is a complex problem, not well understood by policy makers and the general public. The recent Chelyabinsk incident in Russia created temporary international attention but has failed to effectively stimulate public action. The lack of long-term attention to cosmic hazards has resulted in limited funding to defend our planet. Hence, it is hard to realistically address this challenge and achieve the high test and operational readiness needed for an effective Planetary Defense strategy. To address this problem, we have created a set of recommendations for the development of a Planetary Defense Program, for the purpose of contributing to the protection of Earth from asteroids and comets. The SSP15 READI Project focused on threats for which there is only a short-term warning, specifically a warning of two years or less from detection of the object to impact. We have provided recommendations in five areas of Planetary Defense including detection and tracking, deflection techniques, global collaboration, outreach and education, and evacuation and recovery. We have applied this set of recommendations in a narrative scenario to make our report more impactful and engaging. We contrast optimistic and pessimistic outcomes for a comet threat, differing from each other in terms of the level of readiness achieved during the years leading up to the discovery of the threat. In our optimistic scenario, the deflection system has achieved high test and operational readiness. The world's governments have realized the importance of being prepared against cosmic hazards and put in place all of the necessary measures for a successful defense, leading to a positive deflection of the comet. In contrast, in the pessimistic scenario no preparation is done before the detection, and the comet strikes a heavily populated area releasing energy equivalent to 80 times the most powerful nuclear bomb ever detonated. The recommendations that we have identified in this report constitute a roadmap to avoid this horrible outcome, and we believe they should be taken seriously and swiftly implemented.

# Table of Contents

Acknowledgments.....	i
Faculty Preface.....	iii
Participants' Preface .....	iv
Abstract.....	v
Table of Contents .....	vi
List of Figures .....	ix
List of Tables .....	x
List of Acronyms .....	xi
Chapter 1. Introduction .....	1
1.1 The Threat.....	1
1.2 The Project.....	3
Chapter 2. Elements of Planetary Defense.....	6
2.1 Detection.....	6
2.1.1 Introduction.....	6
2.1.2 Current Capabilities .....	6
2.1.3 Needed Improvements .....	7
2.1.4 Enabling Technologies.....	9
2.1.5 Timeline – Detection and Tracking.....	10
2.1.6 Failure Tree Analysis .....	11
2.1.7 Conclusion .....	12
2.2 Deflection.....	12
2.2.1 Objectives .....	12
2.2.2 Current and Proposed Technology.....	12
2.2.3 Proposed Solutions.....	21
2.2.4 Conclusion .....	24
2.3 Global Collaboration.....	25
2.3.1 Initial Policy Objectives.....	25
2.3.2 Current Policy Situation.....	25
2.3.3 Normative Foundations as a Proposed Method for Taking an Action.....	29
2.3.4 Contingency Plans.....	34
2.4 Outreach and Education.....	35
2.4.1 Objectives .....	35

2.4.2 Current Methods .....	36
2.4.3 Proposed Solutions.....	38
2.4.4 Conclusion .....	44
2.5 Evacuation and Recovery.....	45
2.5.1 Introduction.....	45
2.5.2 Objectives .....	45
2.5.3 Understanding the Threat.....	45
2.5.4 Damage Assessment .....	46
2.5.5 Mass Evacuation Strategy .....	49
2.5.6 Shelters.....	51
2.5.7 Recovery Strategy .....	56
2.5.8 Conclusion .....	56
Chapter 3. Comet Scenario .....	58
3.1 Preface.....	58
3.2 Initial Conditions .....	58
3.3 With a Dash of Rocket Science: An Optimistic Scenario.....	58
3.3.1 Pre-detection Phase: 2015-2030 (T0-15).....	59
3.3.2 Detection Phase: January 2030 (T0) .....	61
3.3.3 Tracking and Preparation Phase: February 2030 (T0+1 month).....	62
3.3.4 Deflection Phase 1: June 2030 (T0+5 months).....	62
3.3.5 Deflection Phase 2: January 2031 (T0+12 months).....	63
3.3.6 Deflection Phase 3: October 2031 (T0+21 months) .....	64
3.3.7 Impact and Recovery Phase: January 2032 (T0+24 months).....	65
3.4 Fast Rocks and Hard Knocks: A Pessimistic Scenario .....	65
3.4.1 Pre-detection Phase: 2015-2030 (T0-15).....	65
3.4.2 Detection Phase: January 2030 (T0) .....	66
3.4.3 Tracking Phase 1: February 2030 (T+1 month).....	67
3.4.4 Tracking Phase 2: April 2030 (T+3 months) .....	67
3.4.5 Deflection Phase 1: January 2031 (T+12 months).....	68
3.4.6 Deflection Phase 2: July 2031 (T+18 months).....	68
3.4.7 Deflection Phase 3: October 2031 (T+21 months) .....	69
3.4.8 Impact and Recovery Phase: January 2032 (T+24 months).....	69
3.5 Timelines.....	70

Chapter 4. Discussions and Recommendations .....	76
4.1 Detection and Tracking .....	76
4.2 Deflection.....	76
4.3 Global Collaboration.....	76
4.4 Outreach and Education .....	77
4.5 Evacuation and Recovery.....	77
4.6 Timeline for Implementation .....	79
Chapter 5. Summary and Conclusions .....	80
References.....	81
Appendices.....	94
Appendix A. Outreach Surveys .....	94
Appendix B. Application in ISU Departments .....	96
Appendix C. Current NEO and LPC Detection Projects .....	104
Appendix D. List of Most Relevant Websites About Planetary Defense .....	108
Appendix E. Outreach Game Mechanics.....	109
Appendix F. Existing Evacuation Techniques .....	110



## List of Figures

Figure 1: Global Map of Bolide Events 1994-2013.....	1
Figure 2: Near Earth Asteroids (NEA) Impact Interval vs. Diameter and Impact Energy .....	3
Figure 3: Artist's Concept of NEOWISE Space Telescope.....	7
Figure 4: Path of a comet on an impact trajectory with the Earth.....	11
Figure 5: Failure tree analysis for detection and tracking.....	11
Figure 6: Image taken of comet Tempel-1 67 seconds after Deep Impact hit its surface, photographed by the mission flyby spacecraft. The camera has been saturated by light scattered from plumes of ejecta ....	13
Figure 7: Yields and weights of US nuclear weapons .....	15
Figure 8: Architecture for a vehicle including a thermonuclear device attacking the subsurface layers....	16
Figure 9: Technical architecture of the DE-STAR system .....	17
Figure 10: Comparison of the power delivered by different laser systems over interplanetary distances..	18
Figure 11: An artistic representation of the DE-STAR system.....	18
Figure 12: Representation of the gravity tractor principle on the asteroid.....	19
Figure 13: Representation of the solar concentrator principle: It is a dual reflector system with an indirect-pumped rear laser system. The arrows show the direction of solar radiation pressure on each surface .....	20
Figure 14: Diagram of a mission to rendezvous with an asteroid to paint one side of it and initiate Yarkovsky-effect deflection.....	21
Figure 15: Approximate diagram used for the trade-off of the secondary type of mitigation. Image courtesy of Tim Warchocki .....	23
Figure 16: Plot of near-Earth comets' sizes and relative velocities, with bubble size representing their total energies .....	23
Figure 17: Plot of near-Earth comet sizes and relative velocities, with bubble size representing their impact energy.....	24
Figure 18: Plot of near-Earth comet sizes and relative velocities, with bubble sizes representing their theoretical Earth impact energies .....	24
Figure 19: The idealistic model of Planetary Defense endeavor .....	34
Figure 20: Screenshot from the scenario implemented in KSP .....	38
Figure 21: Mascots Pho (left) and Ash (right) .....	39
Figure 22: Ash (left) vs Smokey Bear (right) .....	40
Figure 23: Ash in his environment vs Smokey Bear in his environment.....	41
Figure 24: Potential Planetary Defense Badge for Boy Scouts.....	42
Figure 25: Comic example.....	42
Figure 26: Disaster Management Roadmap.....	44
Figure 27: (a) Shoemaker Impact Structure, Western Australia; (b) Barringer Crater; (c) Barringer Crater top view; (d) Arizona Meteor Crater aerial view .....	47
Figure 28: Simulation of an asteroid blast showing the area of impact and crater dimensions .....	48
Figure 29: Evacuation Coordination Chart .....	50
Figure 30: Evacuation execution timeline .....	51
Figure 31: (a) Fallout shelter example in Long Island; (b) London underground used as a bomb shelter ..	52
Figure 32: Examples of expedient shelters : (a) blast shelter, (b) expedient blast door, (c) expedient blast shelter shoring, (d) expedient fallout shelter.....	53

Figure 33: Vivos modular shelters example, where each module can support 200 people for 1 year in case of an apocalypse.....	54
Figure 34: Realistic view of the interior of Genesis Project. The 3D visual shows the flexibility of the module to be expanded further if necessary.....	54
Figure 35: Illustration of the DELT arrays engaging Madhusa .....	63
Figure 36: Age distribution of the participants of the survey .....	94
Figure 37: Background of the participants of the survey .....	95
Figure 38: Survey participants' responses to the question "What are NEOs?" .....	95
Figure 39: Radar telescopes: (a) Goldstone 70-m antenna, (b) Arecibo Observatory .....	105
Figure 40: Artist's concept of the WISE spacecraft.....	106
Figure 41: Artist's concepts of the (a) NEOCam and (b) Sentinel space telescopes.....	107

## List of Tables

Table 1: List of pros and cons for the thermonuclear option .....	14
Table 2: TRL Evolution Roadmap for the Hypervelocity Comet Intercept Vehicles (HCIV) .....	22

# List of Acronyms

AIDA	Asteroid Impact & Deflection Assessment	NASA	National Aeronautics and Space Administration
ARM	Asteroid Redirect Mission	NAT	Nuclear Apogee Thruster
ASE	Association of Space Explorers	NATO	North Atlantic Treaty Organization
AT-14	Action Team on NEOs	NEA	Near-Earth Asteroid
AU	Astronomical Unit	NEO	Near Earth Object
BMDS	Ballistic Missile Defense System	NEOCam	Near-Earth Object Camera
CCD	Charge-Coupled Device	NEOCC	Near-Earth Object Coordination Center
CID	Charge-Injected Device	NEOWISE	Near Earth Object Wide-field Infrared Survey Explorer
DARPA	Defense Advanced Research Project Agency	NRC	National Research Council
DELT	Direct Energy Laser Terminals	ORL	Operational Readiness Level
DES	Directed Energy Systems	OST	Outer Space Treaty
DE-STAR	Directed Energy System for Targeting of Asteroids	Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
DNA	Deoxyribonucleic Acid	PD	Planetary Defense
EADP	Emergency Asteroid Defense Project	PHO	Potentially Hazardous Object
EGT	Enhanced Gravity Tractor	R2DE	Responsibility to Defend Earth
ELT	Extremely Large Telescope	R2P	Responsibility to Protect
ESA	European Space Agency	RADAR	RADio Detecting And Ranging
ESO	European Southern Observatory	RSDE	Responsibility to Defend Earth
FEMA	Federal Emergency Management Agency	SAR	Synthetic Aperture Radar
GSLV	Geosynchronous Satellite Launch Vehicle	SDSS	Sloan Digital Sky Survey
HAIV	Hypervelocity Asteroid Intercept Vehicle	SEPP	Synchronized Earth Protection Plan
HCIV	Hypervelocity Comet Intercept Vehicles	SMPAG	Space Missions Planning Advisory Group
IAA	International Academy of Astronautics	SODAR	SONic Detection And Ranging
IADC	Inter-Agency Space Debris Coordination Committee	SSA	Space Situational Awareness
IAWN	International Asteroid Warning Network	SSP	Space Studies Program
IDPAG	Impact Disaster Planning Advisory Group	STEAM	Science, Technology, Engineering, Arts, and Math
IMAG	International Mission Authorization Group	STK	Systems Tool Kit
ISON	International Scientific Optical Network	TML	Threat Mitigation Level
ISRO	India Space Research Organisation	TMN	Threat Monitoring Network
ISS	International Space Station	TMT	Thirty Meter Telescope
ISU	International Space University	TND	Thermonuclear Device
JWST	James Webb Space Telescope	TPP	Team Project Plan
KSP	Kerbal Space Program	TPR	Team Project Report
L1, L2, L3, L4	Lagrangian points	TRL	Technical Rediness Level
LASER	Light Amplification by Stimulated Emission of Radiation	UN	United Nations
LEO	Low Earth Orbit	UN COPUOS	United Nations Committee for Peaceful Uses of Outer Space
LiDAR	Light Detection and Ranging	UN COPUOS STSC	United Nations Committee on the Peaceful Uses of Outer Space Scientific and Technical Sub-Committee
LINEAR	Lincoln Near-Earth Asteroid Research	UNGA	United Nations General Assembly
LPC	Long Period Comet	UNOOSA	United Nations Office for Outer Space Affairs
LSST	Large Synoptic Survey Telescope	UNSC	United Nations Security Council
MAG	Mitigation Action Group	UNSG	United Nations Secretary General
MAOG	Mission Authorization and Oversight Group	US	United States
MIT	Massachusetts Institute of Technology	USA	United States of America
MPC	Minor Planet Center	WISE	Wide-field Infrared Survey Explorer

# Chapter 1. Introduction

All life that we as humans are aware of is contained on or around the “pale blue dot” we call home. Earth is the cradle of life and generally does an incredible job protecting its inhabitants from external threats. Despite a robust atmosphere and magnetosphere, it cannot prevent all hazards from threatening the life it contains. Cosmic hazards come in many forms but our discussion of Planetary Defense will focus on the threats of asteroids and comets. The potential dangers associated with high energy impacts from these objects pose a real threat to life on Earth. At least one of the five major extinction events in the Earth’s past was the result of an asteroid impact, approximately 65 million years ago, and smaller impacts occur more frequently. Figure 1 demonstrates this by showing a map of the bolide events (meteors) recorded around the globe between 1994 and 2013. Earth is constantly bombarded by objects of various sizes, but events such as Tunguska in 1908 (Napier and Asher, 2009) and Chelyabinsk in 2013 (Brown et al., 2013) demonstrate that impacts from larger threats are much more common than the public usually believes. Therefore, it is essential that systems and methods be developed to deal with these hazards, and ensure the habitability of Earth and the survival of the life that it contains.

Current technologies have reached the point where it is plausible for humans to take a proactive role in defending Earth. As such, it is critical for humanity to conduct studies and develop the necessary technologies to protect our planet. It is also essential to ensure that people are educated on the threat so they can make informed decisions. Governments and non-governmental groups need to collaborate at unprecedented levels, and must accept that impacts will occur and be ready to respond to the resulting devastation. Any Planetary Defense Program will require a huge effort, time, and support to be successful, and it demands increased attention now.

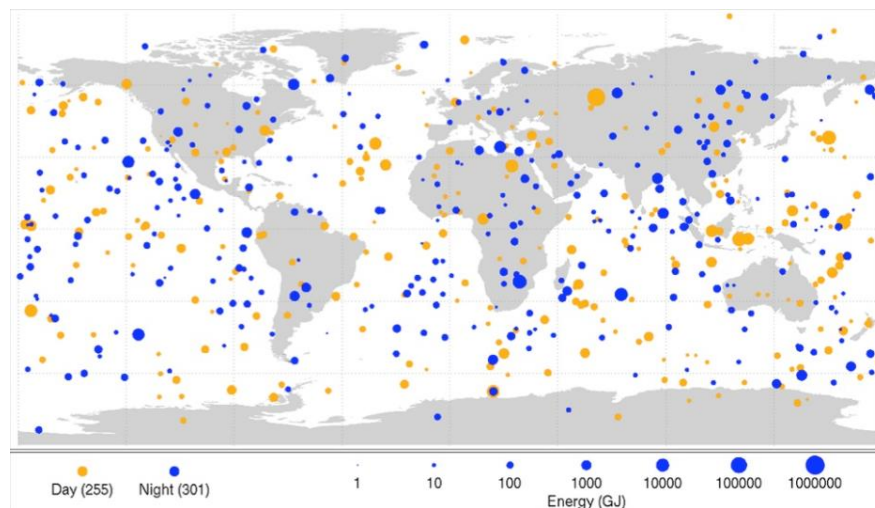


Figure 1: Global Map of Bolide Events 1994-2013 (Source: NASA)

## 1.1 The Threat

In order to contribute to the discussion on Planetary Defense and to propose solutions to the problem, a thorough understanding of the threats, namely Near-Earth Objects (NEOs) and Long Period Comets (LPCs), must be achieved. NEOs are asteroids or comets that orbit the Sun with a closest approach distance to it (perihelion) of 1.3 AU or less (Chodas, n.d.), while LPCs are comets with periods greater than 200



years. Asteroids and comets are thought to be relatively unchanged remnants of the primordial phase of the Solar System formation that failed to aggregate into planets about 4.6 billion years ago.

Most asteroids are rocky bodies, with a minority composed of metal, principally nickel and iron. These celestial objects range from very small sizes (some meters across) to hundreds of kilometers in diameter and generally orbit the Sun in a region between Mars and Jupiter. Other asteroids are located in the outer region of the Solar System, beyond Neptune's orbit. Nearby planets can influence the orbit of these objects and some of them enter trajectories closer to the Sun. Asteroids classified as NEOs can be found in four types of orbits: the Atiras and Amors orbits come close to Earth but never cross its orbit, while the Atens and the Apollos have Earth-crossing trajectories and have a higher chance of impacting the planet. (NASA JPL, 2005).

Comets on the other hand are made of ice, rock, and organic compounds, and are often only a few kilometers in size. They mainly exist in the outer Solar System, in the region between Uranus and Neptune and in the Kuiper Belt, beyond Neptune's orbit. Astronomers believe that the latter comets can be thrown by interactions with the major planets and other stars from a theoretical region called the Oort Cloud, located further out in the Solar System. They can enter into an orbital course around the Sun with any inclination with respect to Earth's orbital plane. These are called LPCs because they orbit the Sun in elliptical trajectories with orbital period ranging from 200 years to several million years. The short-period comets that exist in the Kuiper Belt periodically approach the Sun in orbits with periods of under 200 years with inclinations generally close to Earth's orbital plane (Dones et al., 2004), and they are included within the NEO category if they fulfill the perihelion criterion.

Figure 2 shows the number of expected Near-Earth Asteroids (NEAs) and their estimated impact interval vs. their diameter, the expected impact energy, and their absolute magnitude (their brightness). Various estimations of the population are shown, from a simple mathematical distribution (power law) to accurate measurements from optical surveys. The red solid line represents the number of detected objects as of 2014. Almost all of the biggest objects, greater than 1km in diameter, have already been discovered. An impact from any of these objects could create a global extinction event (Shulte et al., 2010), but none of those detected currently threaten Earth, and their estimated time between impacts is in the millions of years. On the other hand, objects smaller than 20m in diameter may disintegrate in the atmosphere and create no damage on the ground, but impact Earth at least once a century. The most threatening asteroids are then those between 20m and about 500m in diameter. The extremes of this range have either very high impact intervals or very low impact energies, but the objects in between are mostly undetected, which means they can impact Earth with little to no notice, and they can level a city or even devastate a whole region (Brown et al., 2013). The lower impact rate of larger asteroids is offset by the greater effort (in time or in energy) required to deflect them and higher energy released on impact, so overall the objects in the size range of 20m to 500m present a relatively uniform level of threat.

Comets are expected to have a similar mathematical distribution according to size (Lamy et al., 2004) but have much lower impact rates (Weissman, 1982). The same reasoning as for asteroids can be applied to them regarding size and threat, but LPCs present an added challenge: They rarely come into the inner Solar System, and spend very little time there compared to the rest of their orbit, making their approaches to Earth essentially unpredictable. They also have higher velocities relative to Earth and therefore deliver more energy on impact. These two reasons make it necessary to be prepared for comets of larger sizes that asteroids even though a cometary threat may present itself very rarely. Other reports from the International

Space University have previously treated the impact of comets before and showed the need for better preparation against comets (SSP05 TP Cassandra, 2005; SSP07 TP Phoenix, 2007).

An important issue in Planetary Defense contributing to the threat is the lack of information among the general public. We conducted a number of surveys to illustrate this. A high percentage of the surveyed population is completely uninformed of what the term NEO refers to, and does not realize the level of threat that asteroids and comets pose to the planet. The results are summarized in Appendix A.

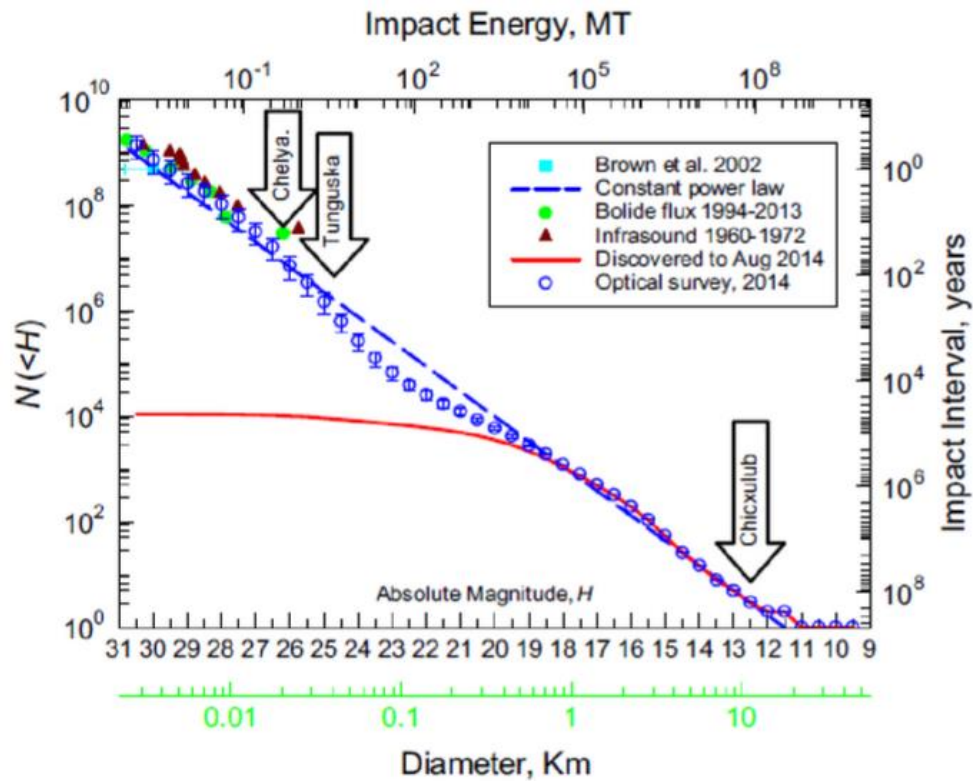


Figure 2: Near Earth Asteroids (NEA) Impact Interval vs. Diameter and Impact Energy (Lubin, P., 2015)

## 1.2 The Project

Understanding the threat we face and the lack of general knowledge clarifies that the scope of this problem is highly complex. From the engineering aspect of Planetary Defense, current technologies need further development. Moreover, to effectively detect and mitigate asteroid and comet threats, we must increase the Technical Readiness Level (TRL) and Operational Readiness Levels (ORL) of current technologies. The human side of the Planetary Defense problem also presents an incredibly complex challenge given the wide range of human interactions required to achieve success. Therefore, it is critical to frame the context of our approach to Planetary Defense by bounding the problem and making it manageable.

We used a specific set of elements as the foundation for our analysis because they enable us to develop solutions for a limited range of problems, rather than a broader perspective of Planetary Defense. The most important bounding factor to our focus is that we are looking at a short-term threat. We constrained ourselves to two years from the time of detection until impact. That does not mean two years from today

but two years from a selected time in the future, 2030. We were able to explore plausible future technologies and methods to be developed until this time.

We chose to look at solutions that address threats within a determined range in size. As mentioned above in Figure 2, asteroids between 20m and 500m in diameter are the most threatening to Earth, but regarding comets it is important to be prepared to deal with bigger sizes. Comets come with much higher velocities relative to Earth due to their highly elliptical trajectories, delivering much more energy than asteroids. LPCs are not detected with much time before they pass near or potentially collide with Earth. They spend little time in the inner Solar System where they are visible. Even if an impact from a bigger object is highly unlikely, the limited warning time and high energy motivated us to ensure that our solutions mitigate objects up to 2km. Our solutions deal with both asteroids and comets, since they represent similar threats to the planet, so our final bounding factor of our scope ranges from 20m to 2km in diameter.

We made the decision to use storytelling and a cometary-impact scenario in the report to engage the reader across chapters consistent with each other, showcase the different steps and obstacles to overcome, and provide both optimistic and pessimistic case developments. A well-written story also has the potential to reach a wider audience if it goes through a plausible sequence of events and a realistic threat.

In order to properly research the problem, we identified five elements of Planetary Defense and looked in depth at potential solutions for each. The topics that we covered are detection and tracking, deflection techniques, global collaboration, outreach and education, and evacuation and recovery. Each of the groups analyzed current and future technologies and methods to develop solutions.

1. **Detection:** The detection of NEOs and LPCs is the first fundamental step in preventing hazardous objects from impacting Earth. After detection, the tracking phase becomes the most important, since a precise orbital determination is fundamental for implementing a successful defense strategy. This is pursued through professional ground and space-based telescopes that observe the sky in the visible and infrared bands. Amateur astronomers also play an important role supporting professional observations. In addition to these, radar observations are performed, enabling very precise orbit determination and characterization of asteroids and comets.
2. **Deflection:** We selected innovative but feasible technical ideas inspired by an extensive literature review of existing concepts. These mainly revolve around the use of thermonuclear devices, and Directed Energy Systems (DES). The need for a highly redundant and robust mitigation architecture led the group to also investigate ground-based solutions that would act as a last line of defense. We emphasized the need to overcome numerous political and economic hurdles to increase the TRL of the proposed solutions. This would allow better preparation and higher confidence when designing Planetary Defense missions. Even though further analyses are required to assess the technical feasibility of the proposed scenarios, we highlight the main needs to increase the chances of success in such missions.
3. **Global Collaboration:** The most important challenge is the establishment of new norms and a legal basis for action in the case of an imminent impact threat. The second challenge would be the creation of an advisory body that would oversee the implementation of a Planetary Defense Program and provide advice to the United Nations Security Council (UNSC). We recommend taking immediate action in these areas because a long time might be required to establish international consensus, and that time is needed for the internalization of our newly proposed norms as a moral obligation.

4. **Outreach and Education:** We aimed to increase interest in Planetary Defense among children and students. Targeting this demographic provides access to future active members of society, and will likely involve their parents indirectly. We believe that having a mascot and using it across different media would be a good way to actively involve children. We took inspiration from the United States' (US) famous "Smokey Bear," used for 70 years to make people aware of fire safety. We also developed two video game ideas using current and potential software to involve children and other age groups to convey basic knowledge of asteroids and comets through an interactive and entertaining activity. We considered an educational campaign as being twofold. First, it brings the threat of cosmic impacts to the general public in a way that provides scientifically accurate information to decrease the risk of misunderstanding and opposition when actions are needed. Second, it contributes to the Science, Technology, Engineering, Arts and Mathematics (STEAM) movement by bringing science and engineering to the youth through the arts, which could in return lead to new creative and innovative approaches to Planetary Defense.
5. **Evacuation and Recovery:** According to the threat characteristics, asteroid and comet impact responses will differ from typical disaster response techniques. In the case of small impacts where the damage will only be local, the response for evacuation or recovery will be similar to the existing strategy for an earthquake or hurricane. A similar method can be used in case of a small to medium-sized threat. With most asteroid or comet threats however, the timely identification of the point of impact seriously affects the successful implementation of evacuation and shelter allocation. The best scenario for saving as many citizens as possible is to start evacuation days prior to the impact. To minimize loss of life and ecosystems, disaster preparations must be developed at different scales, and global collaboration can be useful in the case of large city-killer threats. New techniques for shelter design and remote sensing are also required to assist with recovery efforts. Our investigation of evacuation and recovery shows that this is a critical element of Planetary Defense that does not get enough focus to see significant improvements.

We also established the foundation of the READI Project on the seven ISU departments to provide an interdisciplinary approach. This is further expanded in Appendix B.

The solutions presented in the following chapters are components of a complete Planetary Defense Program that represents practical future methods for protecting the planet and life as we know it.



## Chapter 2. Elements of Planetary Defense

### 2.1 Detection

#### 2.1.1 Introduction

NEOs are both asteroids and comets that approach the Sun with a minimum distance of less than 1.3 AU (Chodas, n.d.). Their search and discovery began in the 1960s, but only in the 1990s did advances in computing power and telescopes enable astronomers to have the tools they needed to fully understand and characterize NEOs (Yeomans, 2015). Several significant NEOs have impacted Earth that caused mass extinctions level impacts. LPCs also pose a threat to the planet when they come into the inner Solar System, so it is necessary to develop detection capabilities to search for NEOs and LPCs that might impact Earth.

The first step to mitigate the threat posed by these objects is to detect them: If we fail to identify them or find them too late, there is very little we can do to prevent their impact. Therefore, it is extremely important to have an effective system that locates and characterizes asteroids and comets as early as possible. This chapter aims to establish a comprehensive program targeted for successful detection and characterization of more than 90% of NEOs. This includes initial discovery, follow-up observations, precision orbit determination, and some level of physical characterization.

After presenting the current technologies already in place for detecting and tracking NEOs and LPCs, and the proposed and in-development ones, we will discuss ways to improve and implement current and in-development detection and tracking strategies, the time needed to achieve this objective, and the failure modes that can affect these technologies. We will also provide insight into the dual-use possibilities for the technologies employed for asteroid and comet searching and tracking, with a special focus on New Space companies and how they can participate.

#### 2.1.2 Current Capabilities

Most of the effort in Planetary Defense currently focuses on detection and tracking of Potentially Hazardous Objects (PHOs). Currently, the larger professional telescopes, which can observe objects at great distances from Earth with greater accuracy, are used to detect NEOs and LPCs but only some of them ever perform follow-up observations. Smaller, often amateur telescopes are usually employed to track these objects after they are first discovered to improve the knowledge of their orbit. Most of the current professional telescopes used for asteroid and comet detection were not originally intended for that function, but are repurposed instruments. Some proposed ground-based missions are exclusively intended for NEO search (Yeomans, 2015).

A number of international contributors such as NASA, ESA, and Roscomos operate the most important ground-based programs used for detection in visual wavelengths. The agencies support a number of relatively small observatories dedicated to NEO and comet detection and tracking in the optical band. NASA controls the only space telescope dedicated to asteroid detection: the NEOWISE space telescope shown in Figure 3. They are also financing the development of next-generation ground telescopes dedicated to NEO and LPC search, and are studying proposals for new infrared space telescopes to increase the detection rate of objects down to 140m in diameter. Appendix C provides a detailed explanation of all these efforts.



*Figure 3: Artist's Concept of NEOWISE Space Telescope (Source: Wikipedia)*

### 2.1.3 Needed Improvements

Current efforts in NEO and LPC detection and tracking are very limited by funding and technical capabilities. We identified a number of goals and requirements that need to be followed to increase the identification rate of asteroids and comets to achieve the performance needed for successful Planetary Defense. These requirements correspond to a number of needs in the current asteroid and comet detection efforts, and will lead to the creation of a Threat Monitoring Network (TMN) that is an essential component of a complete and coherent Planetary Defense Program. Many of these are already proposed by small projects, which is a sign of a positive direction in current efforts for mitigation of the cosmic impact threat.

**Requirement:** Additional infrared space telescopes shall be deployed to increase detection and tracking capabilities; they shall be located at one of the Earth-Sun Lagrange points.

**Rationale:** Visible light can be used for detection, but it does not provide a determination of the size: optical telescopes cannot differentiate a small, bright object from a big, darker one, since they are limited by the albedo (the reflectivity) of the object. However, all asteroids and comets emit light in the infrared according to their size. Thus, infrared provides increased detection capabilities, and can be used alongside optical telescopes to characterize the object. Ground telescopes have limited infrared capabilities, since most of infrared light is absorbed by the water vapor layer of the atmosphere (JWST FAQ, 2015), so a space platform is ideal. The location of the telescope has an important influence on its tracking and detection ability. Telescopes away from Earth provide an advantageous point of view of NEOs, and the observations can be combined with ground-based observations to increase accuracy of the determination of position thanks to the observed parallax. The Earth-Sun Lagrange point L1 can provide coverage of orbits in the Sun's direction relative to Earth (NASA NEOCam, 2015), and L2 has lower thermal constraints for the asset than Earth's orbit, allowing for more sensitive detectors (Farquhar et al., 2004). A complete network for NEO and LPC detection requires a telescope in at least one of those points. While current space telescopes such as the James Webb Space Telescope (JWST) can be used for asteroid and comet detection, their primary function is in scientific endeavors. They are highly in demand by the world's scientific community and it is very hard to justify using them for non-scientific purposes such as the characterization of NEOs for Planetary Defense. Once these telescope have completed their missions, their scientific demand has been met, or their funding has been cut, they are usually shut off and left in orbit. There is the

potential that they can be repurposed for other functions. One example of this is NEOWISE, which was repurposed by NASA for the detection of NEOs after its mission completion in 2009 (The NEOWISE project, n.d.). Although it lacks the operational capability of many of its instruments due to loss of cooling equipment, it is still able to perform NEO detection using certain infrared bands.

**Requirement:** The geographical distribution of ground telescopes shall be improved, extending the coverage capabilities in the southern hemisphere. The time to cover the complete sky from ground stations shall be reduced to at least once a day.

**Rationale:** The easiest way to ensure that all NEOs and LPCs within current capabilities are detected is by scanning the entire sky on a regular basis. The southern hemisphere is also not covered thoroughly by professional telescopes. Most of the telescopes are too small, and the bigger ones are not continuously available for observations. Many threats go unidentified or are detected too late. More funding and personnel should be dedicated to current plans to extend the sky coverage. Follow-up observations (astrometric and physical characterization) are carried out worldwide by professional and amateur astronomers. They are important for short-term alert and for the monitoring of highly hazardous objects. Coordinated cooperation in the ground segment is necessary to optimize the use of this resource. Currently the Minor Planet Center (MPC) is in charge of coordinating asteroid and comet observations among amateur astronomers and small observatories. ESA's Near-Earth Object Coordination Center (NEOCC) is starting to assume the same role in Europe (Minor Planet Center, 2015). These two organizations collect the most relevant data and events on asteroids and comets approaching Earth and monitor the NEO population. This role should be assumed by one single international organization that can more effectively optimize sky coverage, integrate distribute data, and allocation asset usage.

**Requirement:** Sky coverage shall be increased to detect NEOs on an incoming trajectory from inside Earth's orbit.

**Rationale:** The Chelyabinsk asteroid in 2013 reached Earth from the Sun's direction, making it impossible to detect. Ground assets cannot observe during the day, so a space-based telescope shall be deployed to observe angular regions near the Sun.

**Requirement:** Radar capabilities of radio telescopes shall be used to accurately track detected NEOs to determine their characteristics and orbits.

**Rationale:** Use of radar capabilities allows for accurate tracking of objects close to Earth. Goldstone Observatory in California and Arecibo Observatory in Puerto Rico are the biggest radar dishes available as of 2015. These observatories shall increase the amount of time they spend tracking the orbits of known NEOs. Radar observatories shall be constructed in the southern hemisphere to increase sky coverage.

**Requirement:** Algorithms for data processing and object identification shall be improved to reduce or eliminate human intervention.

**Rationale:** Current algorithms for NEO and LPC identification in observations require human intervention (Beasley et al., 2013). These processes shall be made more autonomous and robust to make the process faster and more reliable. Algorithms shall be developed to automatically identify and track objects, determine the orbits and evaluate impact risk to optimize the time of use of the telescopes. Space telescopes can greatly benefit from automated detection algorithms. These can reduce the amount of data transmitted down to the ground station from the telescope, which is a problem for telescopes in orbits far away from Earth such as at the Lagrange points L4 and L5, or in Venus-like orbits (as the Sentinel telescope).

Automated detection and identification would allow for on-board processing of all the images and drastically reduce the amount of data sent to Earth. These automated algorithms could also be used in old images to discover previously observed objects that were missed by human observers.

**Requirement:** Knowledge of the behavior and composition of cometary nuclei shall be increased with further scientific missions to comets.

**Rationale:** Most scientific efforts are currently focused on asteroids. We know much about their composition and distribution, but we lack composition data about comets. This forces us to act on a very small statistical sample and may hinder our efforts to deflect them from incoming trajectories. Comets are a less likely threat to Earth than asteroids, but they approach with higher relative velocities and are harder to detect ahead of time, so their effects can be far more devastating. Efforts on planetary defense should include comets to prepare effective defense mechanisms against them.

### 2.1.4 Enabling Technologies

The creation of a telescope network for asteroid and comet monitoring is possible with current and advanced technologies. These technologies will assist in increased capabilities for detecting and tracking dangerous objects. Creating and maintaining a fleet of space-based observatories can be very costly with current technology. Telescopes require very heavy mirrors, and the sensors lose performance over time due to the lack of active coolant or radiation damage. This problem can be tackled with new technologies that reduce weight and use new materials to improve performance. These technologies are currently being developed:

- Advanced lightweight mirrors reduce the initial mass, and therefore the overall system cost. Examples of these technologies include low-mass membrane mirror optics and liquid surface mirrors. (Roithmayr et al., 2005)
- Modern detectors (such as S-cam by ESA) capable of rapid NEO identification. The S-Cam uses a new optical technology known as superconducting tunneling junctions to count single photons, and at the same time provide spectral information. This data is used to detect and identify asteroids and comets for simplified follow-up observations, cataloguing, and future identification. (Roithmayr et al., 2005)
- New infrared sensors are being developed that have the required sensitivity for detection but can be operated with passive cooling systems, which increase the operational lifetime of the telescope by several years. These sensors would be first tested in the NEOCam telescope. They allow for the creation of a network of long-lived space telescopes that do not require constant replacement, thus being able to monitor the sky continuously. (McMurtry et al., 2013)

We have identified a number of new observational techniques to improve the performance and the observational range of current hardware. New techniques can also be used to increase the NEO detection rate, ease the follow-up observations and tracking, or increase the range of NEOs that can be detected. Some of these are:

- The adaptive optics technique removes atmospheric disturbance (Tokunaga and Jedicka, 2006). This measures the disturbance created by the atmosphere, and then adapts the mirror in real time to correct for it. It is currently used in the most expensive telescopes such as the Very Large Telescope in the European Southern Observatory (ESO, 2014b).



- Shading technologies block the incoming light to allow for observations close to the Sun, thus increasing the area of the sky being mapped. For space telescopes, the shading could be an attached sunshade, an internal disk similar to those used in coronagraphs, or a large deployable shade flying in formation with the telescope.
- In active illumination, a laser array sweeps the area of the sky being scanned, and the same array is pointed back at the expected time of return of the signal in a detection mode. This technique provides many advantages over passive observation, namely precise distance measurement, surface characterization and independence from the object's reflectivity. Lasers in or near the optical spectrum can be used for active searches of the sky. They provide a more focused energy beam and reduce the power requirements for operation. While only a laser array greater than 1km in diameter could be used for active detection in significant areas of the sky, the smaller versions can be extremely useful tracking tools for small asteroids and can scan small sky patches currently out of range of optical telescopes, such as regions near the Sun (Riley et al., n.d.).
- The fly-eye telescope and other wide field-of-view telescopes can allow for observation of the entire sky once a day to search for NEOs and LPCs. Two of these telescopes (one for each hemisphere) and two dedicated follow-up telescopes distributed properly can detect 90% of the objects up to 160m in the first two to three decades of observation, and up to 50% of the objects down to 20m diameter in the first decade (Bernardi, 2011).
- Laser communications can reach data download rates to Earth of about 0.6Gbps at distances as far as the Moon (Buck and Washington, 2013). Telescopes in orbits far from Earth are currently constrained by the data rates achieved with radio communications, so achieving high download rates is an enabling technology for cosmic threat monitoring from space.
- Crowdsourcing detection allows thousands of people to go through each of the observation images in search of new objects. This contrasts with current detection techniques, which are very intensive in human intervention, and for which it is impossible to guarantee that a single person will identify every object that is observed. A statistical analysis of all the results will produce positive detections the same way an expert would do, provided enough people give their input for each set of observations. This increases the ability of the observatories to process the images they obtain. (Beasley et al., 2013)

### 2.1.5 Timeline – Detection and Tracking

The detection phase is the first step in Planetary Defense and therefore very important in the timeline of events. Detection of objects requires a wide field camera to observe large areas in a small timeframe to identify as many objects as possible. The detection is assisted by ground-based optical telescopes to improve the measurements and assessment of their orbits. The days following the initial detection are of utmost importance to confirm the detection as a new object and to track it.

As soon as the observers detect an object, the tracking phase begins. Tracking will take anywhere from a few days up to several months to improve the trajectory accuracy and evaluate the possibility of an impact. Emphasis is put on quickly improving the determination of the trajectory to accurately assess the impact probability, and to create an action plan to mitigate the threat. Tracking is ideally performed with a narrow-field space-based telescope sensor. Along with tracking, the characterization of the object can take place. Here spectrometry measurements can be performed to get the composition of the threat that will give insight into the properties of the object and its origin. Tracking is especially important for comets because they

experience turbulent activity while coming into close proximity of the Sun due to violent outgassing. Especially after the comet has passed through perihelion, it is possible that the comet has fragmented. In the case of asteroids, tracking continues to improve our knowledge of the orbit of the object. Figure 4 shows the trajectory of a hypothetical comet on an impact trajectory with the Earth.

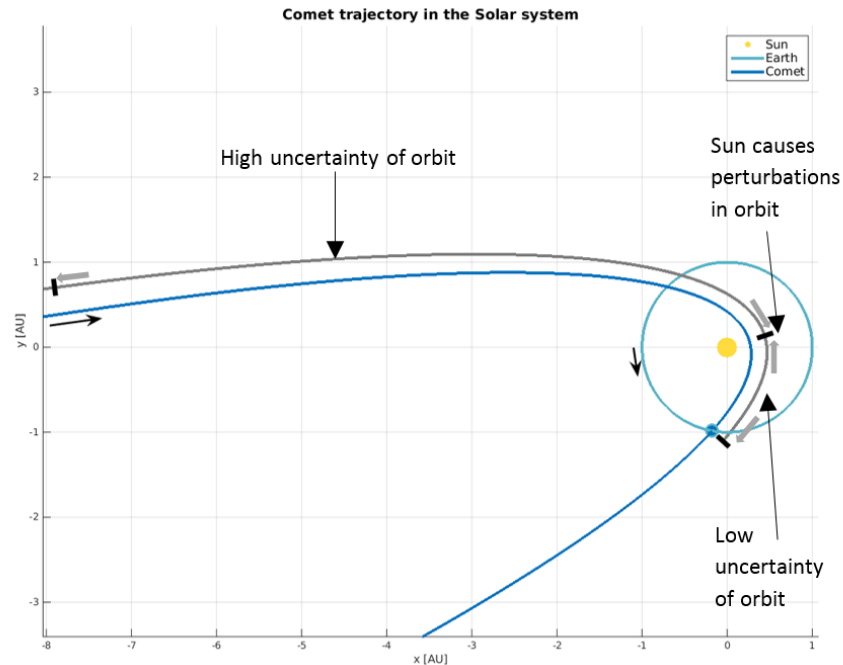


Figure 4: Path of a comet on an impact trajectory with the Earth

### 2.1.6 Failure Tree Analysis

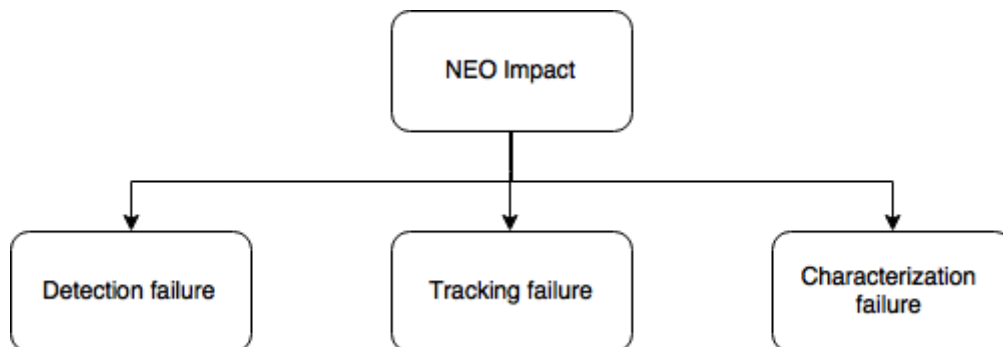


Figure 5: Failure tree analysis for detection and tracking

The TMN requires multiple systems that relate to ground-based telescopes, space-based telescopes, deflection systems, international cooperation, and mitigation. These systems can be defined in a failure tree to identify weaknesses. The top event of the failure tree, as shown in Figure 5, is defined as an asteroid or comet impact. From here the sublevel components are created, which relate to a failure in detection, tracking, or characterization of the threat.

Failure in detection is characterized by equipment failure, not having the proper equipment and instruments, or acting too late. Without detection, the chance of avoiding a disaster is reduced to zero. Also delayed observation of an impending threat can cost valuable time for tracking and deflection and result in a possible impact. The next failure refers to tracking. Observation conditions, such as orbital geometry, or equipment failure can impede the tracking of the threat and cause a delay in procuring the required trajectory information for deflection and evacuation from the affected areas. Finally, there is the characterization failure, which refers to a possible wrong interpretation of the approaching object. In the worst case, astronomers underestimate the size of the object and the proposed deflection is insufficient to prevent the object from impacting Earth.

### **2.1.7 Conclusion**

Detection and tracking is the first step in the protection of life on Earth from hazardous asteroids and comets. To improve our ability to detect, track, and characterize NEOs and LPCs we need to increase the number of telescopes both in space and on the ground. It is not enough to just detect the thousands of asteroids and comets present in our Solar System. Once they are located, repeated observations are needed to determine the probability of impacts with Earth. We need to develop more accurate means of detecting objects at further distances from Earth. Better infrared sensors will help us to determine more NEO and LPC characteristics. We recommend that a comprehensive TMN be created to detect, track, and characterize asteroids and comets to properly assess the possibilities of a cosmic impact.

## **2.2 Deflection**

### **2.2.1 Objectives**

The main technical goal of the READI Project is to design and execute a mission to deflect a comet or asteroid from its course to impact Earth, with a warning period of two years from detection. With an early detailed characterization of the comet it is possible to adjust the mitigation solution and, with sufficient warning time, to design an adapted mission. There will always be remaining uncertainties regarding the internal composition and structure of the object. This is why some deflection techniques involving landing on the comet may be risky or even inappropriate (Carnelli, Ailor and Tremayne-Smith, 2014).

### **2.2.2 Current and Proposed Technology**

#### **2.2.2.1 Kinetic impactor**

The simplest way to deflect an object from its original orbit is the kinetic impactor. A massive object is launched toward the target to collide with it. By the momentum transfer principle, the high-velocity impactor transfers kinetic energy onto the asteroid. On 4 July 2005, NASA's Deep Impact mission successfully collided a hypervelocity satellite projectile with the comet Tempel-1 (NASA/JPL-Caltech/UMD, n.d.). The impact is shown in Figure 6. This demonstrated the navigational capability to impact distant objects at high speeds.

Non-nuclear kinetic impactors are the most mature approach, and could be used in some deflection/mitigation scenarios, according to an analysis of deflection alternatives that NASA conducted in 2007 (NASA Report, 2007). However, such impactors have limited energy and deflection may require more

powerful methods such as nuclear devices. Detection in the early stage is one of the most important factors, since the time to impact from detection dictates the amount of change in velocity of the comet is required for deflection. There are several more techniques based on kinetic impactors that will not be elaborated on here (Gibbins and Vasile, 2011; Carusi, 2005).



*Figure 6: Image taken of comet Tempel-1 67 seconds after Deep Impact hit its surface, photographed by the mission flyby spacecraft. The camera has been saturated by light scattered from plumes of ejecta (NASA/JPL-Caltech/UMD, n.d.)*

#### **2.2.2.2 Thermonuclear Devices (TNDs)**

TNDs are the most readily available alternative to kinetic impactors. The characteristic dimensions of the affected zone, even for explosions of medium yield, are comparable to the dimensions of the comet itself, making it a feasible option with today's technologies. TNDs are a matter of great political conflict any time they are considered, but our project focus requires them. As we mentioned in the introduction, we are studying deflection techniques for asteroids and comets with sizes ranging from 20m to 2km in diameter. The objects on the high end of that range are too big to be deflected with kinetic impactors, and nuclear devices have the greatest energy density available. A complete Planetary Defense Program must include TND as a deflection tool. Table 1 shows a list of pros and cons for the thermonuclear option.

Deflecting an asteroid or a comet is a form of energy transfer. Delivering a huge amount of energy to the surface of the object would affect its overall momentum (Howley, Managan and Wasem, 2014). The risk of breaking the object and dealing with a new set of fragments that could be potential new threats remains a major concern. (Winterberg, 1981; De Geer, 1991; Alger, 2009; Panofsky, 2003; Nguyen, 2009; Cote, 1996).

The power of today's available nuclear devices that could be used in space against NEOs or LPCs ranges from tens of tons (equivalent mass of TNT) to about 50 megatons (Mt) (GlobalSecurity, 2011). Figure 7 shows the current yields and weights of US nuclear weapons.

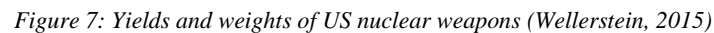
*Table 1: List of pros and cons for the thermonuclear option*

Advantages	Disadvantages
Higher concentration of energy necessary to modify the momentum of the object (10 to 100 times more effective than other solutions)	International concerns and public policy issues that must be addressed by UNCOPUOS
High TRL for space applications	Possible environmental issues
Low cost of integration	High mass of the device
Experience of the international community with this technology	Possible dual use of this technology

Many issues must be tackled to select a feasible and standard thermonuclear system to deflect asteroids and comets (Ferguson and Potter, 2004; Yusuf, 2009):

1. Assessment of the number of dangerous cosmic bodies and their probability of collision with Earth
2. Assessment of the time required to detect and identify objects as hazardous
3. Understanding of the object's motion in the immediate vicinity of Earth, penetration of the atmosphere, detailed dynamics during impact, and assessment of the local and global consequences of the collision
4. Estimation of the required energy for deflection or fragmentation
5. Consideration of the needed nuclear devices, delivery means, and optimal regime of action
6. Assessment of the consequences of the impact of fragments of an object that had been fractured by a nuclear explosive
7. Consideration of the ecological consequences for Earth and for the space environment





Two main solutions are available for designing space missions that use TNDs for NEO or LPC mitigation:

- 
- 15

An explosion in space is inherently different from an explosion on Earth. The main differences are associated with the absence of an atmosphere, the complex shape of the object, and the object's extremely weak gravity and possibly complicated composition. The determination of the orbital parameters of the object is critical. At a distance of 1 Astronomical Unit (AU) it will be necessary to determine the speed with a relative accuracy range between  $10^{-5}$  and  $10^{-4}$ . If the object is detected at a short distance from Earth (0.1 to 0.01AU), the only possible countermeasure would be shattering it into many fragments by devices of 1 to 100Mt yield, depending of the objects final composition.

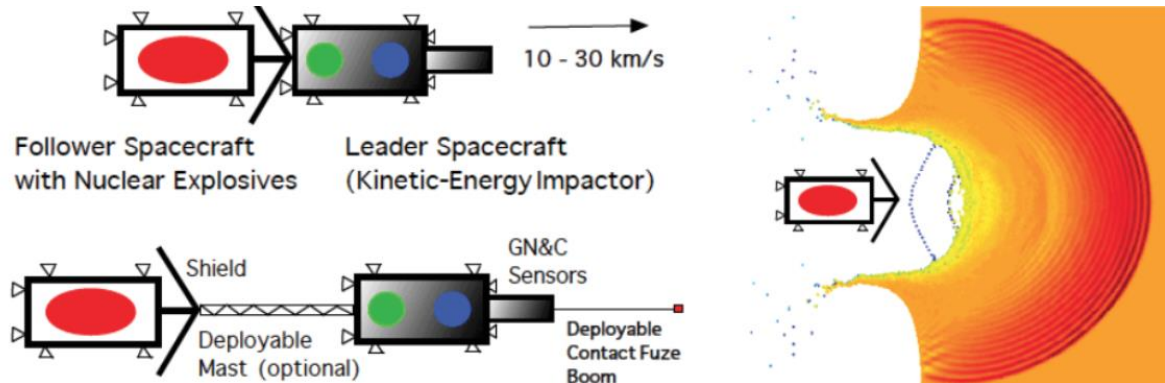


Figure 8: Architecture for a vehicle including a thermonuclear device attacking the subsurface layers (Wie, 2013)

### 2.2.2.3 Directed Energy Systems (DES)

Previously the subject of science fiction, DES have begun to be applied for military use, and have been proposed as an advanced method for diverting a NEO or an LPC from its trajectory (Vasile et al., 2014; Hughes et al., 2014; Lubin, 2013; Claude JPP et al., 2010).

The idea is to create a laser beam and amplify it using electrochemical devices so as to produce a beam that has enough power to ablate the surface of the threat and vaporize its materials. The laboratory of Prof. Philip Lubin at University of California Santa Barbara has been researching the effect of high-powered lasers on a variety of materials, including asteroid-resembling basalts. Their conceptual Directed Energy System for Targeting of Asteroids and exploRation (DE-STAR) device shown in Figure 9 and Figure 11 would combine advances in space photovoltaic panels and laser technology to target a directed energy beam at asteroids or comets that threaten to hit Earth (Hughes et al., 2013).

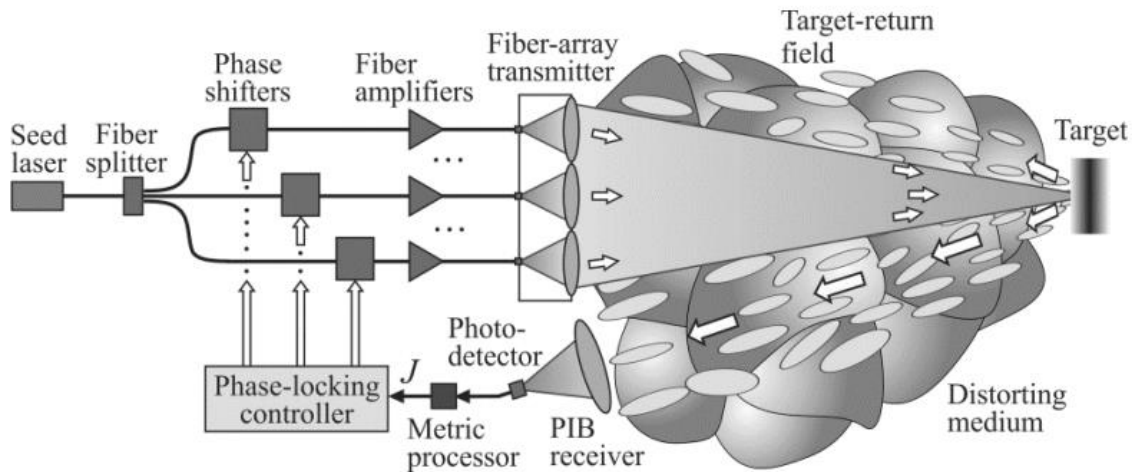


Figure 9: Technical architecture of the DE-STAR system) (Hughes et al., 2013)

A phased array of lasers would focus the energies of multiple smaller beams onto the surface of a target. Based on state-of-the-art deployable solar panels, an array of 1km across could provide enough power to be effective at distances up to 1AU. If the target can be hit with  $1\text{MW}/\text{m}^2$  for periods of a few seconds to a minute, the material will reach temperatures over 2000K and begin to sublimate. A 10km array system could focus its beam on a spot 30m across at 1AU as a conservative estimate (Lubin et al., 2015). Vaporized material will expand rapidly and generate a thrust cone perpendicular to the surface, producing forces of a few hundreds of Newtons. Phased arrays offer the advantage of extremely fine beam steering and the ability to engage multiple targets while allowing modular scalability. For example, lasers based on ytterbium-doped optical fibers lead to a remarkable 83-87% optical efficiency. Using solid-state lasers for all components reduces the chances of breakdown and unit size, increasing the power to mass ratio.

A space-based DES powerful enough to vaporize rock over 1AU away presents obvious problems as a dual-use technology. In the wrong hands, the system could be used against targets on Earth, posing potential roadblocks to its development and deployment. However, agencies could also use the technology as a means of generating propulsion for solar sail vehicles, concentrating photon pressure over long distances to reach relativistic speeds (Bible et al., 2013).

The architecture of a space-based DES could include one or several spacecraft located outside of Earth's atmosphere. The system could start even when asteroids were still far away, giving them enough time to operate if they are already in place and ready to be used. By knowing the size of the asteroid that needs to be deflected, the heat of vaporization can be assessed. This determines the power level needed over the activation time to evaporate the target's surface. As shown in Figure 10, it is easier to ablate a comet than an asteroid. Only a power flux of  $500\text{W}/\text{m}^2$  is required for a typical comet made of ice and other volatile materials, as opposed to the  $10\text{MW}/\text{m}^2$  necessary for a classical asteroid. Having a phased array and accurate steering mechanisms makes it possible to point the laser precisely and even target multiple spots or fragments. The overall system is modular and easily scalable. The cost of the overall architecture and its dual use possibility remain the major hurdles against its development in space.

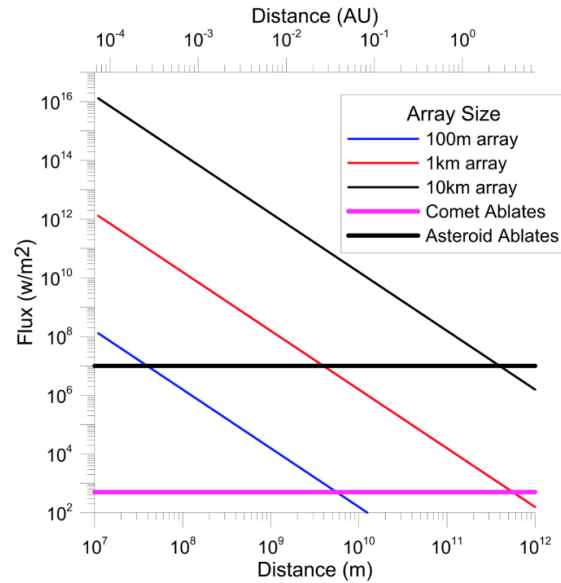


Figure 10: Comparison of the power delivered by different laser systems over interplanetary distances (Johansson et al., 2014)

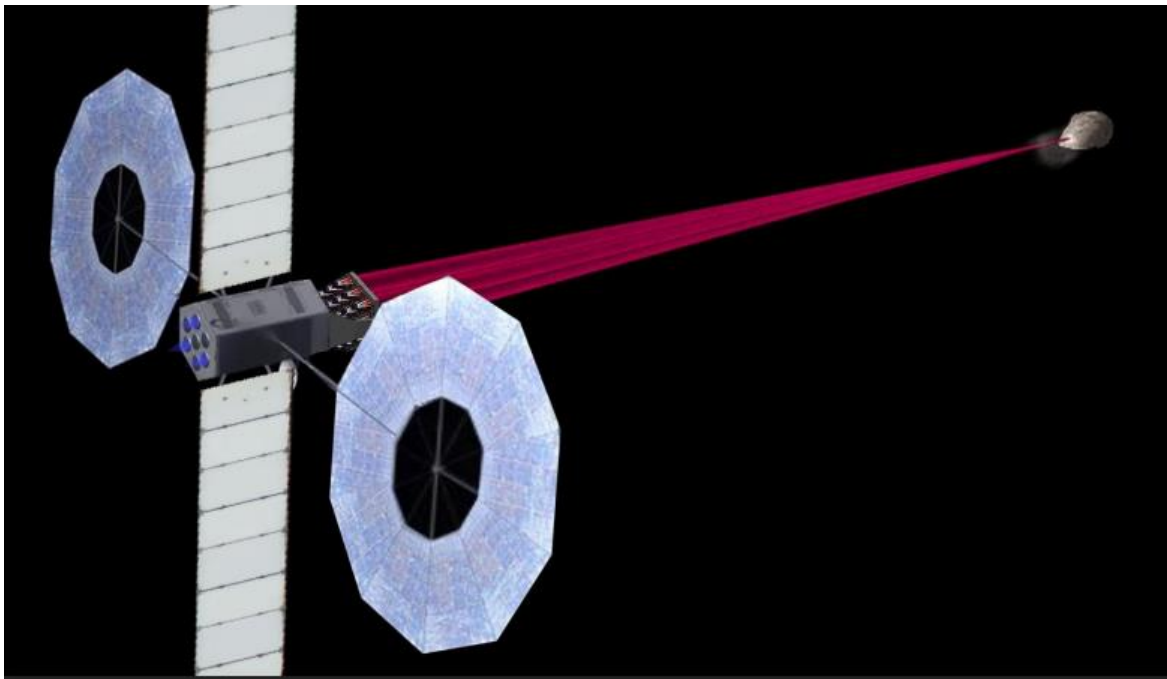


Figure 11: An artistic representation of the DE-STAR system (Johansson et al., 2014)

By extrapolating the current results of the DE-STAR system, it is possible to design a system that would be able to deliver a power of  $50\text{MW/m}^2$  to a threat at a distance of 1AU (Johansson et al., 2014).

If space-based high-power lasers are found to be untenable because of the engineering problems related to extremely large structures, or due to policy issues, it is possible to deploy them as a ground-based system. Atmospheric distortion may be compensated using adaptive optics (Thangavelu, 2015a). On the other hand, the polar regions of the Moon could also offer sites for laser-based Planetary Defense (Thangavelu, 2015b).

#### 2.2.2.4 Gravity tractor

The concept behind a gravity tractor, represented in Figure 12, is to impart a small force onto an object using the gravitational pull of a spacecraft that is kept in close proximity by powered propulsion. If the object could be accelerated to change its velocity by just 1cm/s a decade before impact, it could typically be diverted from its impact course by one Earth radius (Mazanek et al., 2015).

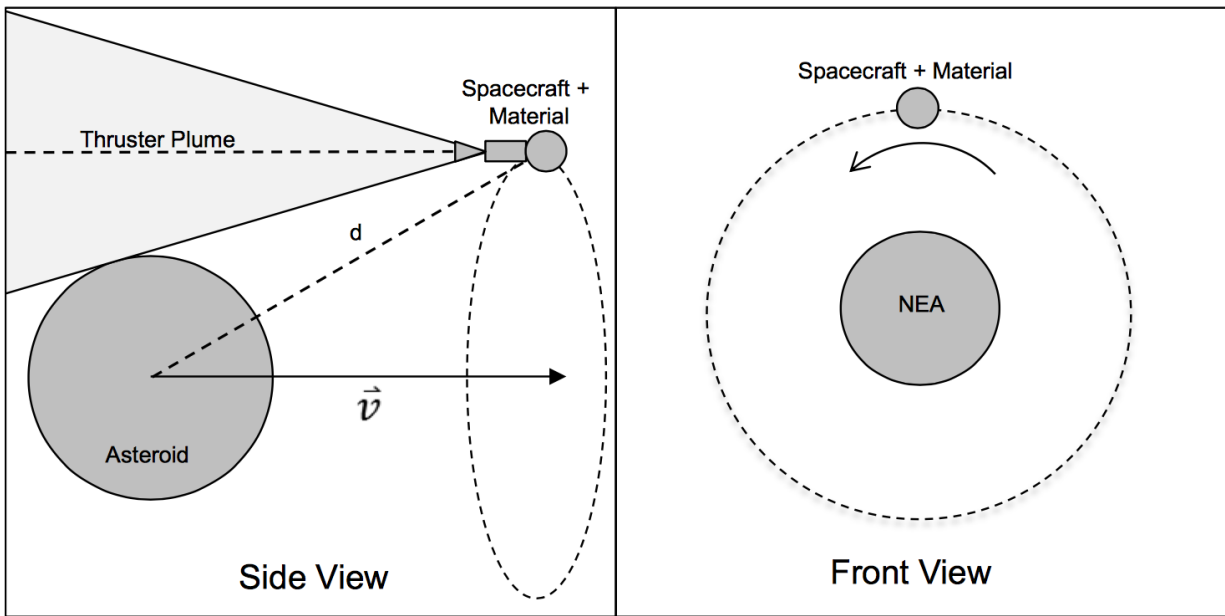


Figure 12: Representation of the gravity tractor principle on the asteroid. (Mazanek et al., 2015)

A more recent version of this, the Enhanced Gravity Tractor (EGT) presented at the 2015 International Academy of Astronautics (IAA) Planetary Defense Conference, involves a robotic mission that would extract or lift tens to hundreds of tons of material from the surface of an asteroid. The loss of mass of the asteroid and increased mass of the tractor would result in a deflection that is 10 to 50 times more efficient than that of the original concept, allowing response times within a decade (Mazanek et al., 2015). This concept has been proposed for testing during NASA's Asteroid Redirect Mission in the 2020s, and some detailed research also has been done in the past several years (Hyland et al., 2010; Gong, Li and BaoYin, 2009; Nazirov and Eismont, 2010).

#### 2.2.2.5 Solar concentrator

A solar concentrator would use one or multiple arrays of concave mirrors to focus sunlight onto a precise spot on an asteroid or comet, as depicted in Figure 13. Once the surface reaches approximately 1800K the sublimating material would generate thrust via an ejecta plume. One advantage is that no additional propellant would need to be carried, although maintaining effectiveness at increasing distances from the Sun would require even bigger mirrors. The concentrator would need to be much closer to its target than a DES, putting it at risk of contamination from the ejecta plume dust covering the mirrors.

A more advanced concept proposes a combination of solar concentrators and indirect, rear-pumped semiconductor lasers to beam the light onto the surface of an asteroid (Vasile, Maddock and Summerer, 2009). A swarm of up to about five spacecraft would overlap their focused beams to produce the



temperatures necessary to generate a plume, with the advantage of being able to act from a distance of many kilometers. Solar-pumped lasers for asteroid and comet deflection are an active area of research, but they require spacecraft to rendezvous with the threat, and a constellation of solar-pumped laser spacecraft would still need many years to deflect the target (Merikallio and Janhunen, 2010; Gritzner, 2006; Kahle et al., 2006).

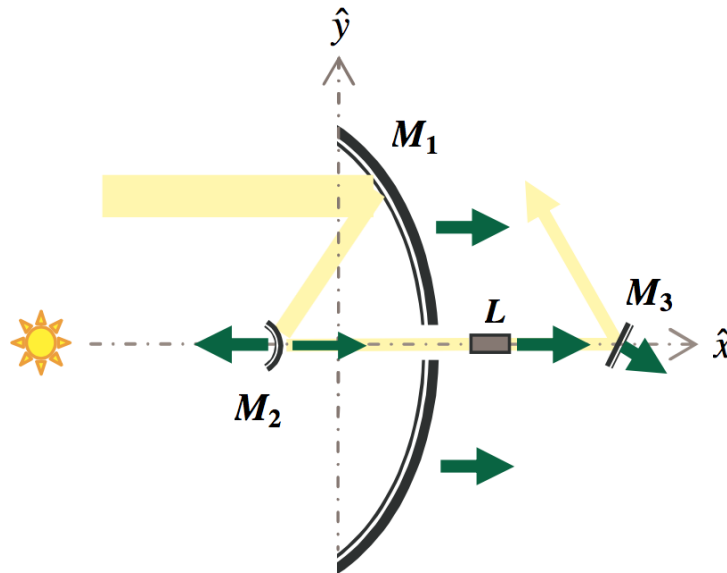


Figure 13: Representation of the solar concentrator principle: It is a dual reflector system with an indirect-pumped rear laser system. The arrows show the direction of solar radiation pressure on each surface (Vasile, Maddock and Summerer, 2009)

#### 2.2.2.6 Asteroid Painting (Increased Yarkovsky Effect)

An innovative “slow push” technique has recently been proposed that consists of painting part of the target either white or black to change the force generated by the solar heating, as depicted in Figure 14. This force imbalance between the illuminated and dark sides of the object is known as the Yarkovsky Effect, which results in slowly pushing the object away from its initial trajectory (Farnocchia et al., 2013).

Asteroid painting seems like a very promising way to mitigate the threat of asteroids, but with such a slow-push technique, the efficiency of the approach and possible unintended consequences must be seriously considered. First, the acceleration of the painted object is inversely proportional to its diameter. That is to say, a larger object will experience a weaker force. Any successful results in the laboratory need to be tested carefully in a practical application. Second, the stability of painting composites for long applications is another potential problem. This technique will inevitably involve the risk of aging of the painting material under the extreme environment of space.

Painting has an additional insurmountable disadvantage regarding its application to comets. Along with the dissolution and sublimation of the ice that generates the tail, the paint on a comet will be peeled away from the surface almost instantly during a close approach to the Sun.

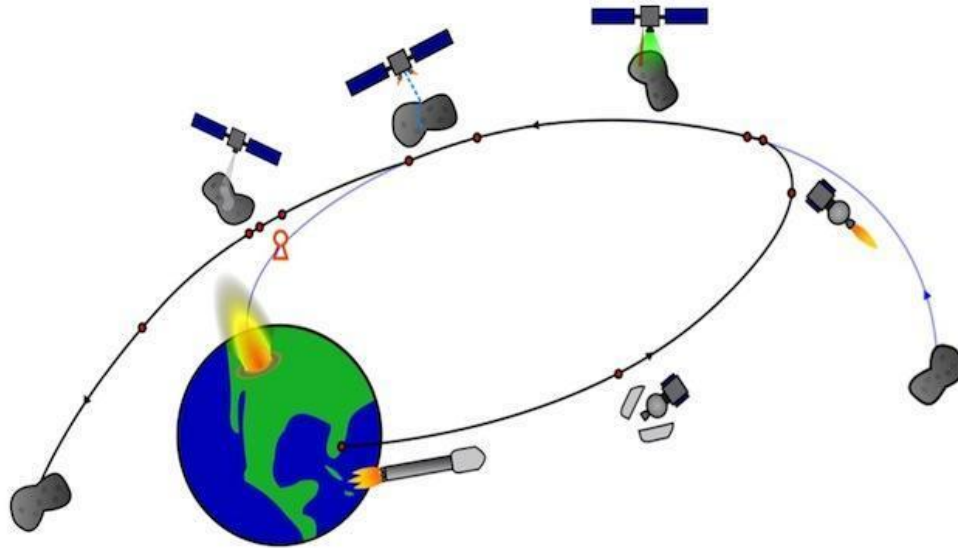


Figure 14: Diagram of a mission to rendezvous with an asteroid to paint one side of it and initiate Yarkovsky-effect deflection (Mann, 2013)

### 2.2.3 Proposed Solutions

Across several reports, NASA has outlined different options, a few of which have involved using nuclear explosives to deflect the threat away from Earth. After reviewing several deflection techniques, we have concluded that the use of a TND is inevitable. However, we suggest the use of a DES as a sustainable mitigation architecture: high-energy lasers can heat up the target's surface and vaporize some of its materials. The main advantage for using this system as a primary mitigation technique resides in the possibility to have a standard Planetary Defense structure ready to operate and to be used for multiple threats.

Table 2 depicts the current conditions for Hypervelocity Comet Intercept Vehicles (HCIV). We also propose some requirements for a roadmap to increase the TRL for HCIVs.

For redundancy, TNDs can be used as a secondary mitigation option. The force from the explosions could impart enough momentum to nudge the asteroid in a different direction or disrupt it into smaller fragments that are easier to handle (Johansson et al., 2014). We used the diagram in Figure 15 to determine the trade-offs of this mitigation technique.

We have taken orbital information from the JPL Solar System Dynamics database (JPL, 2015) about periodic comets that have passed within 0.5AU of Earth over the past 100 years and that astronomers suspect will pass within this distance in the future. Within this set, we have calculated the total kinetic energy and the theoretical impact energy of comets with known nucleus diameter using their maximum velocities at perihelion and relative velocity to Earth. We assumed an average comet density of  $0.6\text{g/cm}^3$  and estimated the total mass based on the common two-bubbled 'peanut' cylinder shape of most known comet nuclei. We adjusted the estimation of the mass to roughly match comets of known mass such as comet 1P/Halley and 67P/Churyumov-Gerasimenko, which is being studied in great detail by the Rosetta and Philae spacecraft.

Figure 16, Figure 17 and Figure 18 in section 2.2.4 show the size of the comet used in the scenarios in Chapter 3 (Madhusa) relative to a range of comets taken from the Small Bodies Database passing within 0.5AU (JPL, 2015). The numbers in red represent the diameter of the comet's nucleus in kilometers. The comet from our scenarios has a high velocity compared to those of the same size in periodic orbits, and therefore the relative velocity is a challenge for any deflection methods. However, we can see that efforts to deflect a relatively small body pale in comparison to what would be required to deal with other objects. The threat-space diagrams are designed to give perspective on the scale of the threat and what we are prepared for today compared to what we may have to face in the far future.

Table 2: TRL Evolution Roadmap for the Hypervelocity Comet Intercept Vehicles (HCIV)

Technology to be considered	Initial Conditions	Requirements to be upgraded to TRL 9
<b>TNDs</b>	<p><b>TRL 6.</b></p> <p>Based on the necessity of maximal energy transfer to modify the momentum of the object, the existing capabilities will be based on an evolution of the device known as B41/Mk41. These were based on the developments from this device between 1960 and 1963. Showing a yield of 25Mt for a weight of up to 5,000kg per device.</p>	<ul style="list-style-type: none"> <li>• Reduction in weight</li> <li>• Efficiency of yield</li> <li>• Isolation</li> <li>• Fusing</li> </ul>
<b>Momentum transfer (Nuclear Propulsion)</b>	<p><b>TRL 4.</b></p> <p>Follow details from the Orion Project propulsion method.</p>	<ul style="list-style-type: none"> <li>• Erosion of pusher plate</li> <li>• Temperature absorption</li> <li>• Spalling</li> </ul>
<b>On-Board Software</b>	<p><b>TRL 5.</b></p> <p>The HCIV will be manufactured for a real-time autonomy domain, and therefore the on-board software must be highly qualified.</p>	<ul style="list-style-type: none"> <li>• Autonomy</li> <li>• Auto-navigation</li> </ul>

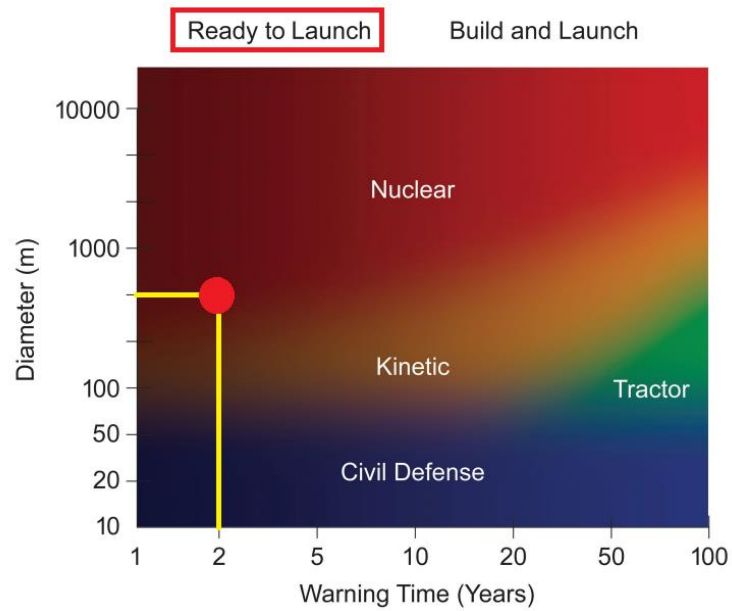


Figure 15: Approximate diagram used for the trade-off of the secondary type of mitigation. Image courtesy of Tim Warchocki (National Research Council et al., 2010)

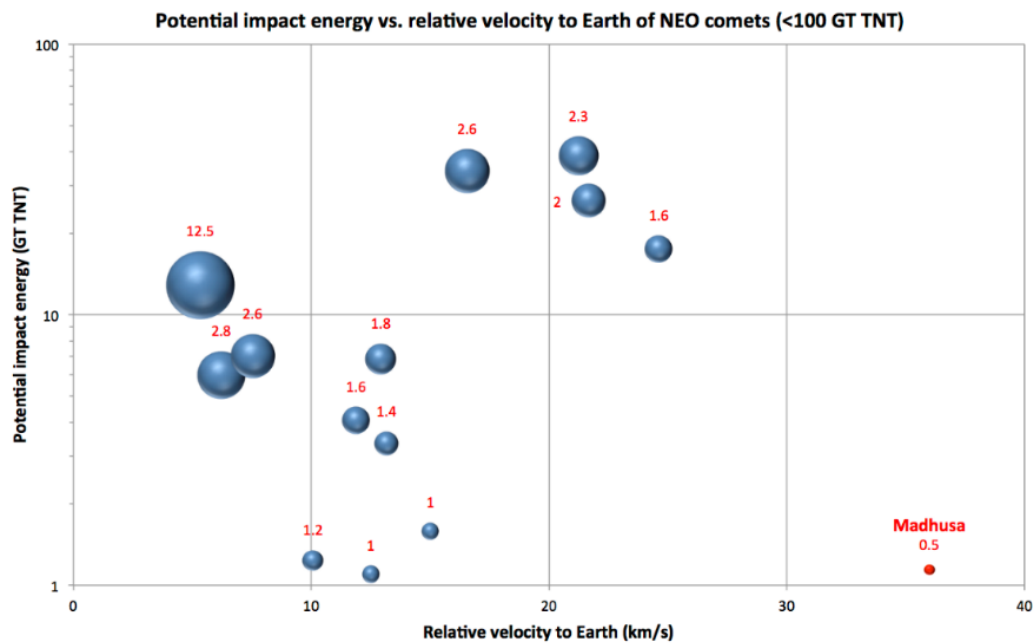


Figure 16: Plot of near-Earth comets' sizes and relative velocities, with bubble size representing their total energies

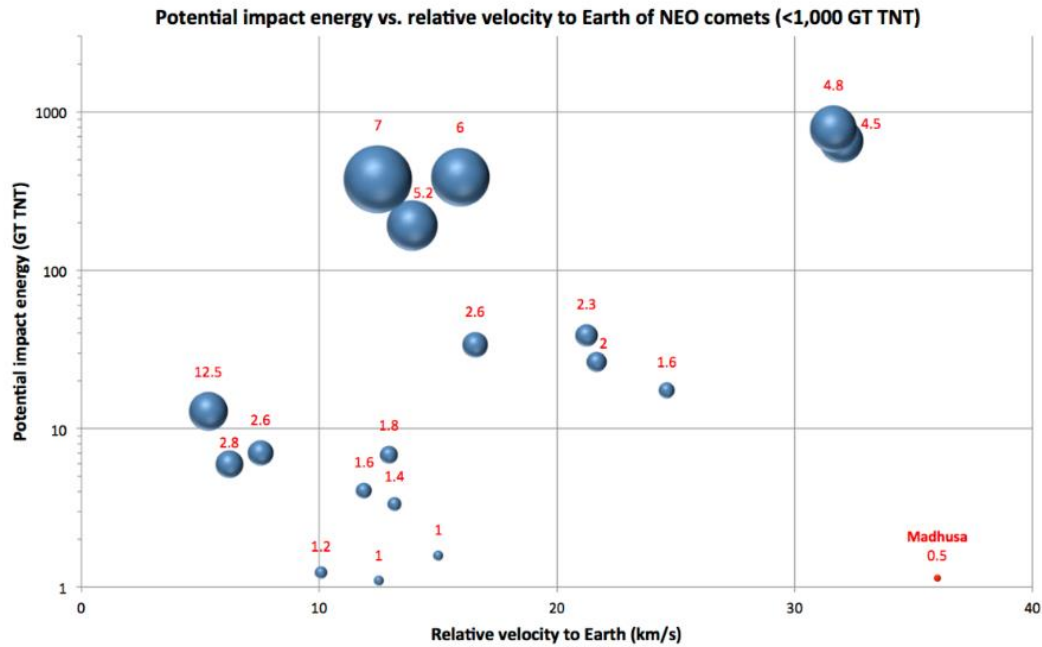


Figure 17: Plot of near-Earth comet sizes and relative velocities, with bubble size representing their impact energy

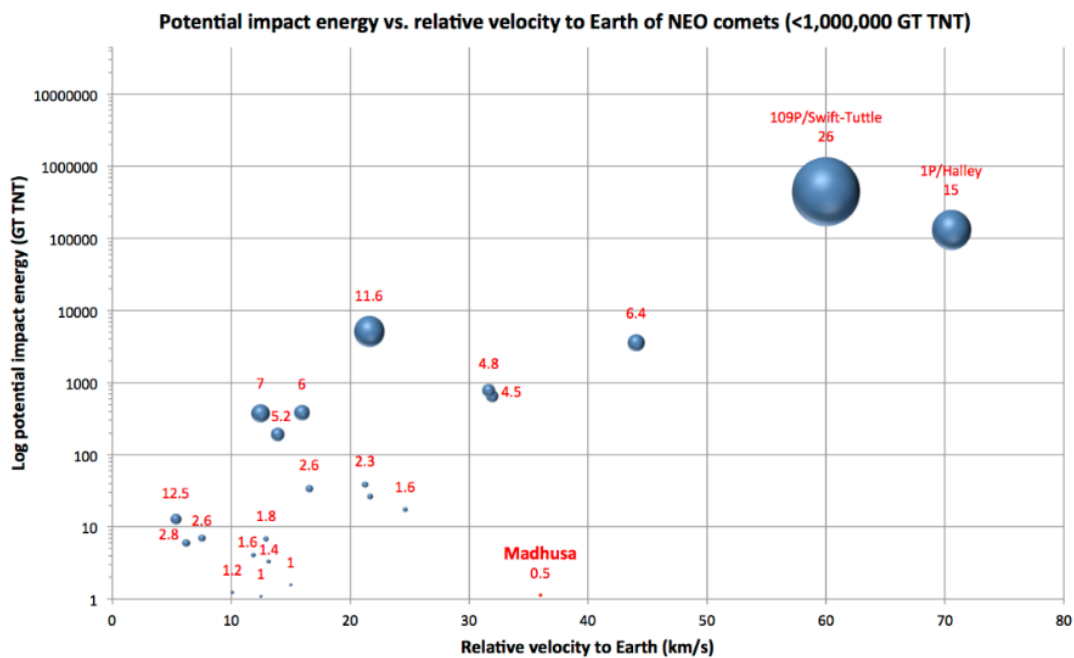


Figure 18: Plot of near-Earth comet sizes and relative velocities, with bubble sizes representing their theoretical Earth impact energies

## 2.2.4 Conclusion

Since we are studying different methods for the same purpose, redundancy is within our reach in an ideal case, as we may use one deflection method as a backup plan for another or simply to reinforce its effects.



Disruption and deflection are both possible ways to prevent an object from reaching Earth, and both are possible if decision makers take action ahead of time.

Relevant agencies should enhance several technologies in case of failure in some parts of the systems. For the nuclear option, authorities should set up several ready-to-launch nuclear missiles. Furthermore, officials can launch more than one rocket at the same time to ensure deflection of the target in case one explosion is not sufficient or successful.

As a last resort in case of a short-term warning scenario or in case the threat has not been deflected and is about to impact, we can intercept the comet using nuclear explosive devices and fragment it in a suborbital trajectory to reduce the impact damage.

## **2.3 Global Collaboration**

### **2.3.1 Initial Policy Objectives**

There are two primary objectives undertaken in the area of global collaboration relative to Planetary Defense. The first objective is the development of new norms related to Planetary Defense, the second objective is the proposal and its acknowledgment by the United Nations Security Council (UNSC) through the creation of a Mitigation Action Group (MAG). The United Nations (UN) is the best place to initiate efforts to surmount this challenge of defending Earth from NEOs and LPCs. The UN has been able to create a historically unprecedented political environment for discussion and conflict mediation, and now, the time has come to use the UN as an arena for a previously unimaginable objective – to defend Earth from asteroids and comets.

The UN should apply itself to the objective of creating a new norm to defend Earth simply because it can; we have the necessary technology to defend Earth and thus it is our duty to do so if a situation requiring action occurs. Although the UN has experience dealing with crises of global implications, this new challenge has many new and unfamiliar aspects. After World War II, the UN had the goal of building trust among nations, and the current lack of trust is the greatest challenge facing any kind of global defense action in the future. If there is a chance to build this trust before a NEO is detected on an Earth impact trajectory, there is no reason to postpone doing so. This is not a case of a conflict between nations, but of a common threat to all nations, and we should unite to face it. Asteroid and comet impacts are likely to pose a threat that is not territorially defined. States' sovereignty is less crucial in this situation. This common threat should unite nations as Immanuel Kant predicted two hundred years ago in his work "Project for a Perpetual Peace" (Kant, 1796). We might create an environment that can limit international conflict in the future by solving a problem that threatens all of us. We believe that we can achieve our objective by applying humanity's morality to a higher and broader level by deliberate creation of a new norm – The Responsibility to Defend Earth (R2DE). This norm should guide the progressive evolution of international law.

### **2.3.2 Current Policy Situation**

Since 2001, the Action Team on NEOs (AT-14) established by the UN Committee on the Peaceful Uses of Outer Space (COPUOS) has formulated proposals on how to establish an international framework for impact disaster response and deflection missions. In December 2013, the United Nations General Assembly (UNGA) voted for the establishment of two advisory groups: the International Asteroid Warning Network

(IAWN), for detection, and the Space Mission Planning Advisory Group (SMPAG), for action planning (UNOOSA, 2013). In contrast to what AT-14 suggested, the Impact Disaster Planning Advisory Group (IDPAG) was not established, and the Mission Authorization and Oversight Group (MAOG), one of the three core elements proposed by Association of Space Explorers (ASE) was not listed in the proposal of AT-14 (Schweickart et al., 2008).

UNGA also agreed that “the existing UN COPUOS would monitor threats from asteroids and help plan and authorize a deflection campaign, if necessary” (Netburn, 2013), and in the purpose of SMPAG, it is stated that “in the event of a credible impact warning by the IAWN, the SMPAG would propose mitigation options and implementation plans for consideration by the international community” (SMPAG, 2013).

With the establishment of IAWN and SMPAG, the basic framework for global collaboration in response to the threat from asteroids and comets has been partially constructed. If there is a threat detected by IAWN, it is still not clear how the international community would implement these action plans.

How UN COPUOS would authorize a deflection and how the international community would consider the mitigation options and implementation plan are unknown, since no clear structures have been proposed yet. From this point of view, Schweickart, the B612 Foundation Chair described the measures adopted by the UN as a skeleton without meat or muscles (Netburn, 2013). For more information about the B612 Foundation see the Space Management and Business section in Appendix B.

### 2.3.2.1 The Dilemma

The UN COPUOS-led global collaboration structure presents several challenges, especially for taking deflection and mitigation actions. There is currently no political will to do so, due to the fact that the impact threat is not taken seriously by states. “No government in the world today has explicitly assigned the responsibility for planetary protection to any of its agencies” said Rusty Schweickart (quoted according to Moskowitz, 2013). These challenges include the following:

1. No high-level leadership. There is no country that wants to voluntarily initiate the creation of a deflection and mitigation mission entity.
2. Technical uncertainties. No observed asteroids or comets have yet been confirmed to be on a collision course with Earth. The SMPAG has held three meetings and there has been no deflection or mitigation plan proposal.
3. UN COPUOS, as a Committee reporting to the 4<sup>th</sup> Committee of the UNGA, has to make decisions by consensus. The groups that it has established have advisory functions but not action functions. The deflection missions will most likely be accomplished using technology that can be easily understood as weapons. This issue is outside of the comfort zone of UN COPUOS and would draw the attention or intervention of other, higher-level authorities.

Some experts are not convinced that UN COPUOS can develop an adequate framework for international decision making and coordinated actions; the current situation is not desirable (Potter, 2015). Even UN COPUOS itself, in its 2015 session, presented that the technical work of IAWN and SMPAG would have to be complemented by high-level political decision making mechanisms so that measures to counter an emerging threat could be implemented in a timely and effective manner (UN COPUOS, 2015).

### 2.3.2.2 Mitigation Action Group (MAG)

According to the proposals of the ASE, the MAG should be created now as a recommendation-making and action-taking structure to lead and coordinate deflection and mitigation missions. There are several paths toward the establishment of such a group.

#### A. Collective Defense Initiative

The UNSC may be the appropriate organization to take the initiative to establish the MAG, since the UNSC is in charge of all issues related to international peace and safety, and is the only body in the UN that can authorize military actions through resolutions. There are two ways to start this initiative:

Plan A: UN COPUOS makes a proposal and the UNGA votes to make a recommendation to the UNSC, leading to the establishment of the MAG.

Plan B: The UN Secretary General makes a recommendation to the UNSC, leading to the establishment of the MAG.

The MAG could be a permanent body under the UNSC, or under both the UNGA and UNSC. The advantages of this path are that, by using the practices and procedures already existing within the UN system, international deliberations will be made and the consensus achieved will guarantee the legitimacy of the MAG and the transparency of its actions. We do not believe that the UNSC would ever be willing to pass critical decision making authority to the MAG. Therefore the MAG should make recommendations on topics such as technology deployment in space to the UNSC and coordinate and lead the mission on its behalf.

The disadvantages of this option are that UNGA needs a two-third vote among its member States, and the UNSC may not agree to the recommendations of the UNGA if there is a veto. The processes of the UN system may result in a long time to reach a decision. For instance, it took 12 years to establish of IAWN and SMPAG to their current state.

The UN has neither the budget nor its own (military) troops to implement a deflection mission. The UN will have to invite its member states to voluntarily offer all necessary resources to lead a collective defense action, even with the establishment of the MAG. Deployment of weapons of mass destruction in space is not easily done, as the Outer Space Treaty (OST) bans these weapons in space. This part of the OST will have to be modified, if humanity is to defend itself from asteroid or cometary threats by these means.

#### B. Multilateral Defense Initiative

Besides the UN system, another option is for spacefaring states to take initiative in the establishment of the MAG. As SMPAG mentioned in its terms of reference, UN member states, especially those with the capabilities to engage in a possible planetary defense mission, already share a number of common interests in NEO threat identification and mitigation (SMPAG, 2015).

Within UN COPUOS, the Inter-Agency Space Debris Coordination Committee has gathered the main space agencies and could serve as a base for such an initiative. The International Space Station (ISS) implementation model could serve as a reference to make the participants accountable for arrangements.

The advantages of this path are:

1. The main spacefaring states who would play the major role in Planetary Defense would know what needed to be done.
2. It may be easier for a MAG acting on behalf of spacefaring states to obtain agreement.
3. It is more flexible: Since no UN intervention is needed for the establishment of MAG, it may get stronger support from the participating states.

The disadvantages of this option are that without the UN, there is less transparency and the MAG may be contested by the other countries, or even the UN itself. Also no state presently wants to be the initiator of this organization.

### C. Legitimizing MAG

Although the MAG may be established within or without the UN, approval by the UN would legitimize its activities, especially when it plans to manipulate NEOs or LPCs with technology that can be abused as weapons.

There are two ways to obtain such approval. The first would be a resolution of the UNSC, and should there be a veto, the second would be a resolution of the UNGA (UNGA, 1950). There is always the possibility of taking action without UN approval but this would seriously violate the UN charter and may incur political repercussions.

### D. MAG Functions

We recommend that the MAG should be an advisory and coordinating entity specifically working on the deployment of deflection and mitigation missions to avoid an impact. It should have the following functions:

- Use the detection results from IAWN and planning proposals from SMPAG to make recommendations to the UNGA/UNSC concerning required actions
- Coordinate and distribute the deflection tasks among member states
- Lead the deflection campaign
- Coordinate with IAWN, SMPAG, and other entities for mitigation plan implementation

### 2.3.2.3 Potential Improvements under Current Structure

The following is a list of recommendations for change that can take place within the existing norms and structures of the UN.

- International decision making depends on the will of nations. UN entities should engage with national decision makers by sharing their activities in the area of cosmic-impact threat research.
- Any actions that contribute to transparency and confidence building should be held as a priority, especially among influential nations, as transparency will be essential to success in defending Earth.
- Stakeholders should obtain political agreement before establishing the MAG, within or without the UN system.
- Use existing NEO cases to persuade national space agencies or the international community to make a significant investment in this area. For example: As a result of a set of hearings by the NASA Advisory Committee following the Chelyabinsk explosion in 2013 in conjunction with a

White House request to double its budget, NASA's Near Earth Object Program funding was increased from \$4 million in Fiscal Year 2009 to \$40 million in the Fiscal Year 2014 budget.

- Review international space laws to take into consideration the legal issues raised by Planetary Defense.
- Enhance detection capabilities to give confidence to decision makers.

### 2.3.3 Normative Foundations as a Proposed Method for Taking an Action

In 1995, the UNGA decided that the international community has the Responsibility to Protect (R2P) people of any state if that state fails to protect them from atrocities such as genocide, war crimes, and crimes against humanity or ethnic cleansing. States do not possess sovereignty when it comes to the basic human rights of their citizens. Human rights have been put above the principle of states' sovereignty for fifty years following the adoption of the UN Charter, and during that time we have witnessed several multilateral actions that have helped to save people from the sorts of atrocities mentioned above. This initiative has changed the international community's perspective on humanity as a principal subject for security. We propose the use of R2P as a starting point for our policy recommendation, because we believe that saving humanity from mass extinction should be seen as a similar moral and ethical obligation. We do not know whether an asteroid or comet is on a collision course with Earth right now; the last two decades of research, including NASA NEOWISE observations, tell us that we do not know how many PHOs are really out there. Statistics have changed significantly, and the threat of asteroids or comets impacting Earth has become indisputable. Since we are aware of the potential threat right now, we have an irreversible ethical obligation to act.

We propose the consideration of a new norm called the Responsibility to Defend Earth. This norm has several distinctions from R2P:

1. R2P puts human rights above the sovereignty of states; in R2DE, there is no isolated sovereign state in the area where the action would take place, yet an action might have an impact on all states without distinction.
2. R2P regulates relations between states; R2DE might save all humanity and does not have an impact upon any one state in particular if the mission is successful.
3. R2P resolves a threat through the success or failure of a particular state, so it reacts to an action or an inaction of that state. R2DE reacts to a common threat where no other states might play a reasonable opposing role (there cannot be national interests regarding celestial bodies as they belong to humanity in general according to the OST).

We propose five phases of this endeavor, where each phase raises different dilemmas, but also brings some additional challenges that might or might not help the international community to cooperate. The whole policy strategy is based on the belief that the initial phases contain fewer dilemmas in the international security dimension, thus, there is a great opportunity to build trust between nations willing to cooperate in this undertaking. This endeavor also provides incentive for superpowers possessing critical technologies or a capability to build them. These superpowers will have to take seriously the threat and collaborate with one another if we detect an asteroid or comet on its way toward us.

#### 2.3.3.1 Common Threat and the Way Forward

As Immanuel Kant stated in his 1795 "Perpetual Peace," it will be nature that will force humans to cooperate in peace. It is imperative for the sustainable security of humanity to reflect the Kantian philosophy of a



shared human moral community and aim our efforts at a collaborative project that will address a fundamental threat to humanity.

We have the ethical obligation to act precisely because we have reached the level of technological advancement that allows us to act. From that perspective, R2DE should provide a “normative foundation” for action. It should be a responsibility to learn about potential NEO threats, to share that knowledge, and to act to mitigate them. This ethical obligation can be achieved cooperatively without the UN, but the UN should provide a controlled roadmap for unilateral action if wide political consensus is not possible. It is better to enable the superpowers’ ability to act on their own through the establishment of norms, rather than to block it completely and force them to act absolutely without the legitimacy of international law. A nation behaving under the duty of R2DE acts in the interest of humanity, a norm of self-preservation that should be respected, as outlined in Article 51 of the UN Charter. The unilateral action of a superpower, which is not under minimal control of other nations may destabilize international relations and threaten world peace; thus cooperative action is in the interest of all.

We propose the following structure and procedure and believe that it would establish international trust and move humanity forward from global governance to a global government structure which applies strictly and only to the area of Planetary Defense. There is one important and indisputable need why humanity must consider this move: Anything deployed in space in defense of Earth can be abused and thus must be under control of all. This initial move can be a deployment on the far side of the Moon, which does not face Earth. It is in our best interest to create an environment where such technologies cannot be abused and in which the abuse of such technology is not a concern, because it is under the control of those who represent us all. It is our responsibility to create a global structure that everyone trusts, despite how naïve it may seem at present.

Each of the following phases has uncertainty that may increase trust and motivation in some cases and decrease it in others.

### **2.3.3.2 Phase I – Space Situational Awareness**

Defense planning under uncertainty is common in the field of national security strategy. Research has not proven the existence of a relationship between the focus in national defense planning and a rational assessment of the security environment. Increased uncertainty in a threat usually leads to higher attention; it follows that decreasing the uncertainty of an asteroid threat by refining its trajectory with increasingly precise measurements might lead to less attention to the threat. From that perspective, considerations such as unpredictable space collisions between objects, sudden release of comets from the Kuiper belt or gravitational resonances should be understood as it is these uncertainties that might stimulate the interest of states to perform appropriate defense planning. The constructivist approach is more than welcomed here and the policy recommendation would be focused on open securitization (Buzan et al., 1998) so as to avoid negligence due to the low probability of impact, as an impact can pose an extinction level threat to humanity. Constructivists see the world around as an opposite to rationalists, they share the conviction that both reality and knowledge are socially constructed; they are more products of our thinking, using symbols of language and concepts thus the reality and knowledge are produced by interpretation rather than having rationally observable basement (Carlsnaes et al., 2002). By proposing a new norm, R2DE, we outline policy that could lead to a desirable future reality. Securitization is a process during which states transform subjects into a matter of security by using language and other constructivist related production of knowledge. In our application here, the threat of asteroid does not need to be existent, the point is produce a strong enough

movement that will “solidify” the threat of asteroid so that it becomes a matter of security from national security perspective. Actively paying attention to these aspects of the threat will increase the interest of policy makers, regardless of how much uncertainty astronomers actually have about a potential threat. Uncertainty in the detection phase is the key to developing trust between nations. During this activity, no action taken would significantly influence the national security of any participating nation. All nations have the same opportunity to contribute during the detection phase. Trust, and the avoidance of mistrust due to fear of cheating, are the keys to international cooperation (Jervis, 1999). Trust can be treated as a commodity in the standard model of a market economy (Dasgupta, 2000), which can be created by the active participation of respected subjects. All scholars of international relations, regardless of their school of thought have their arguments as to why states cooperate; here, we adopt a “constructivist” position to criticize realistic anarchic perspective (Wendt, 1992) and to promote the constructivist way of norm creation (Tannenwald, 2005) as a method to produce policy that helps states cooperate to address a global need. In the realistic perspective, states exist in an environment where no higher authority exists. This situations puts states into an anarchic interrelations as no authority can judge their disputes; they live in constant antagonism and suspicion. Classical realists do not believe in significant powers of UN or socially constructed norms that influence states' behavior. In their perspective nothing other than power is important in global politics. We take the constructivist perspective because we believe that during the time of uncertainty we have to significantly and precisely explain what the consequences of possible threat from outer space are while the whole process of deflection is very unclear.

### 2.3.3.3 Phase II – Technological Development

Building observational infrastructure on Earth and throughout the Solar System would be a huge investment requiring multiple nations to invest a lot of money into a system that should be operated cooperatively. No observation system can threaten any nation if there are no secrets that any nation is trying to hide. Information gathered through it can be used for a wide variety of purposes, Planetary Defense included, but it has potential applications to asteroid mining as well (Andrews et al., 2015).

If the project follows our experience with the construction of the ISS, we should also consider making some parts mutually dependent. Technological interdependence during this phase can help link cooperating teams and can lay the foundation for trust in future phases when it will be critical to international cooperation. The approach, of using milestones that are dependent on the participation of several nations is a means of generating the cooperation needed in future phases. Cooperation during technological development will significantly lower the threat of dual use technology, thus it can build trust between the cooperating nations. The threat of dual use technology is lowered by cooperative development and operation. The construction of planetary defense infrastructure for observation and detection and the development of deflection capabilities are two different matters. Observation and technological development can be considered to be similar phases from the perspective that trust between nations is a core policy outcome for both. There are two different approaches to technology in space security theory that are usually viewed as two sides of the same coin. The first approach comes from optimist scholars that believe technological development can bring peace as was thought by scientists from the United States of America (USA) during the 1950s regarding nuclear technology and freely available electricity in the future resulting from it. The second approach, technology determinism has exactly the opposite view. Advanced technology brings changes that are unpredictable and might lead to world destruction if deployed in space (Moltz, 2011).

Wise selection of technology is one of the critical challenges that we have to face early in the process. The need to develop bigger nuclear weapons against the asteroid or comet threat might proceed under the need of Planetary Defense, though even in a collaborative manner it may cause more challenges to our security than the outer space threat itself (Melosh, 2015). Despite these challenges we will probably have to proceed with the development of nuclear devices as they are widely accepted as one of the best and most reliable solutions. On the other hand, deployment of huge lasers at the Earth-Sun Lagrange points L4 and L5 might be an interesting solution. They can be used for deflection of asteroids coming from the ecliptic plane of the Solar System, and comets coming in at high angles. Lasers can be easily directed to any required location, similar to a telescope. The very advantages of locating a laser at these places (L4 and L5) might be considered absolutely unacceptable because they can be directed toward Earth. From this perspective, lasers are very dangerous because of their quick operability; nuclear weapons, on the contrary, have to be sent back to Earth and that is an easily observable action against which there is a long time to take counter measures. Nevertheless, taboos in international relations are persistent (Price, 1995) and will play a significant role during the decision making process.

The development of technology does not necessarily bring peaceful results, as described earlier in this section. Yet, it is our responsibility to proceed with such development and to build trust. This double-sided consideration represents the challenge that we must face in Phase II. It is more plausible to experience tensions here than anywhere else, as success here leads to success later, when humanity will have to stand strong together.

#### **2.3.3.4 Phase III – Defensive Infrastructure Deployment**

As has been discussed, the deployment of defensive technology against asteroids or comets will be a complicated task and a global concern of all nations. As we proposed, deployment could take place after years of cooperative action regarding detection and successful technological development. The UN will be facing the question of whether the UNSC is an appropriate body for decision-making; however, no other options are viable. Reform of the UNSC has been studied in depth without any meaningful result (Global Policy Forum, 2015) and establishment of something like the MAG with a capability of prompt decision making in the area of Planetary Defense will certainly cause permanent members of the UNSC concern about their potential lack of veto capability in this situation. We can easily deduce from this experience that the UNSC will not be significantly reformed and that, according to historical experience, the UNSC will approve only the non-threatening actions unless Earth is under imminent threat.

The following three technical methods were proposed by our engineers in the chapter concerning deflection methods: 1) Nuclear detonation in space; 2) Space-deployed super lasers at L4 and L5; and 3) Ballistic defense consisting of conventional and nuclear arms that might disintegrate the asteroid or comet to avoid one extreme impact as a last resort.

The Ballistic Missile Defense system (BMD) deployment in Europe and promoted by the USA has created a lot of distrust between the USA and other states, especially Russia. Arguments that the BMD is aimed to deflect rockets from Iran or other countries openly threatening other states (e.g. Israel) did not convince Russia that this move was not a hostile act on the part of the USA, the North-Atlantic Treaty Organization (NATO), and their allies (Hynek and Stritecky, 2010). The years following the idea of a BMD being deployed in the Czech Republic and Poland have brought dangerous distrust, because Europe has not been on the brink of war for many decades and the world might be on the brink of nuclear conflict again (Fischer, 2015). Current political situations do not provide us with an arena to change international law to allow the

deployment of nuclear or laser armaments in space, and the history with BMD can serve as further analysis of this move. On the other hand, BMD as a last resort for Planetary Defense is a reasonable method that should be included on the policy roadmap, so that it might become reality.

Another important need of central global decision making over Planetary Defense is deployment in space; however at the current time this does not seem like an achievable reality. We have come to the conclusion that the trust between nations developed during the first two phases is critical and that this policy has a chance, especially if we take the perspective that the current political situation is more a product of a few disillusioned statesmen (Byman and Pollack, 2001) than of a systemic process, as realists would certainly argue (Waltz, 1979). We have decided to take the position that the deployment of Planetary Defense technologies around the world or in space is unachievable without a globally-appointed governmental structure (MAG) that should be based on a reformed UNSC.

#### **2.3.3.5 Phase IV – Being Prepared**

Two options for humanity are to be prepared or to be unprepared. By preparedness, we describe a situation where states can easily and smoothly predict the next steps of other nations and where we have an established global governmental framework that can make decisions related to Planetary Defense that are acceptable for all in a relatively quick manner. We understand that this is an extremely idealistic position, but we decided to take the position of visionaries rather than realists, as we believe that new threats have to be dealt with using a new perspective, and that global threats should not be addressed by a single superpower. Unilateral action can be avoided through concerted effort and concerted means, wills, and capabilities to act under indisputable trust among all.

We also see two possible outcomes from this situation. The first is the proposed concerted action under a newly established global agency or under the current global governance represented by the current structure of the UN. The second is the unilateral or isolated decision of one or more of the most powerful nations to act without regard for international consensus. We understand the second option to be one that should be respected, but avoided if possible. As we have mentioned, such action can be respected as a consequence of the Article 51 of the UN Charter, even though the article mentions armed attack. The right of self-preservation might be the key of its extensive reading as some states have already pleaded this right.

#### **2.3.3.6 Phase V – Failure**

In the pessimistic scenario in Chapter 3 Section 4 we describe a possible chain of events leading to a mission failure. We also recognize several kinds of failures. The first failure would be the inability of the international community to reach consensus leading to unilateral or multilateral action without appropriate resolution by the UNSC and without global collaboration. This scenario might lead to unimaginable political consequences, with a world war being a possible result.

The second failure would be partial inability to reach consensus leading to disorganized or incomplete actions with unpredictable consequences in deflecting the asteroid or comet. In this scenario, a possible strong action by a superpower after a partial failure is very likely and we elaborate on this in our pessimistic scenario found in section 3.4.

Each failure includes an evacuation and emergency plan, discussed in detail by our colleagues in section 2.5. A resolution by the UNSC or any other kind of governing body is very likely in this case as the UN usually does not have trouble with consensus when it comes to purely humanitarian operations. We

recommend that each state work to avoid the potential ethical dilemmas caused by humanitarian crises that would result from a failure scenario.

A summary of the phases proposed in this section is shown in Figure 19.

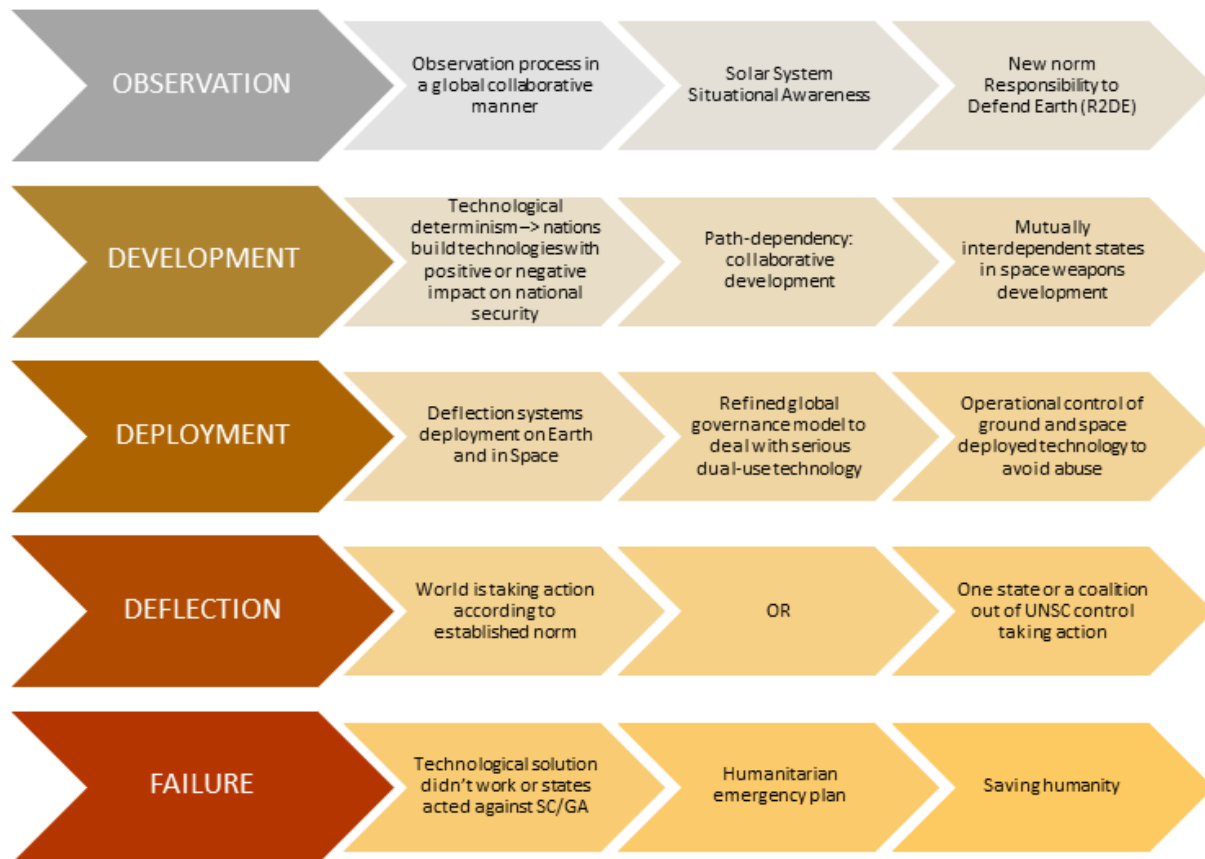


Figure 19: The idealistic model of Planetary Defense endeavor

### 2.3.4 Contingency Plans

Contingency plans will be necessary if the existing norm of R2P is not applied to the domain of Planetary Defense well in advance of an imminent threat. In this case, it is unlikely that the UNSC will approve any testing activities until the test becomes the final deployment of the deflection system.

These contingency plan deployments would likely be rationalized using Article 51 (right of countries to engage in self-defense), as we have already mentioned. This has been done in the past, for example, by the USA's rationale for attacking other nations in response to the terrorist attacks of 11 September 2001 (Dudziak, 2003). A unilateral response to the threat from a comet or asteroid could be justified in a similar manner.

It is also possible that there may be multiple potential launch windows for a deflection system. In this case, it would be easier for the UNSC to delay approving the implementation of a response. The lack of approval could be used to aid in justifying a unilateral response. At a minimum, it is likely that capable nations would choose to build (if not use) a deflection system. This could include preparing all of the necessary systems but not actually launching them. It might also include deployment, because it is safer to deploy untested

technology when one has the opportunity to develop and implement another plan later if the initial deployment does not succeed.

If a nation chooses to respond unilaterally, it might motivate the UN to suggest the sharing of information openly among nations, calling for global cooperation and collaboration for future activities. It is uncertain whether or not sanctions would be placed upon the acting nation until after the threat was known to have been mitigated, if at all, because the timeframe could be quite extensive.

If a state or non-state actor responded unilaterally, the UN would be motivated to call for all capable nations to collaborate on a contingency plan that may be approved by the UNSC at the very last moment that deployment is possible.

Because a unilateral response in the case of an imminent threat has the potential to be necessary, the following questions should be carefully considered:

- What probability of impact would trigger a capable nation to decide to take unilateral action without approval from the UNSC or the UNGA?
- What are the key policy-oriented decision points in determining whether a nuclear or non-nuclear deflection method should be used?
- How would the UN respond if a country used a non-nuclear deflection method without approval and what are the political ramifications of such a decision?
- How would the UN respond if a country used a nuclear device without approval and what are the political ramifications of such a decision?
- What effects would unilateral action have on transparency and confidence-building measures?

We recommend the further consideration of these contingency situations by the UN and space faring nations.

## **2.4 Outreach and Education**

### **2.4.1 Objectives**

Outreach and education are critical to ensuring that the global public and people in positions of authority are informed well enough to make intelligent decisions about Planetary Defense. Informing the general public can be performed in multiple ways including workshops, conferences, or events such as the Asteroid Day (Asteroid Day, 2015), however these usually address people that work within the field or are somehow interested in space. We decided to focus on a younger audience, that being children and students from 6 to 15 years old. By addressing this generation, parents will likely get involved as well, which leads to a wider audience than one could expect. Moreover, the youth from around the world represents the leaders and decision makers of tomorrow. If they are not properly informed of the threats and hazards they will face, they will be poorly equipped to meet those challenges. Developing knowledge early in life is therefore essential as children move through their lives. To that end, we are focusing our efforts on reaching out to adolescents from around the world to increase the awareness on the asteroid and comet threat in an approachable and entertaining way to instill life-long learning.



## 2.4.2 Current Methods

### 2.4.2.1 Internet Review

Existing websites that deal with the NEO and LPC threat present various types of information to the general public, and official information can be obtained from agencies and non-governmental organizations (e.g. ESA, or NASA). Other sources of information include non-profit organizations such as the Secure World Foundation, the Spaceguard Foundation, or the National Space Society. Additionally, websites are used as platform for successful conferences such as e.g. the Planetary Defense Conference website. Information on the outcomes of the exercises held during this biannual conference can be found there. The Emergency Asteroid Defense Project and the Sentinel Mission are examples of sources for information on projects that are non-governmental initiatives from scientists and entrepreneurs around the globe with an operational objective in the detection or deflection of NEOs and LPCs.

To get the global public involved, it is usually advantageous to have visually appealing data. During the research, we came to the conclusion that the Minor Planet Center website, an initiative led by the International Astronomical Union, is the best option when it comes to accurate data and visualizations. The website provides datasets about all the minor planets, including NEOs and LPCs. A recent hackathon hosted by the MPC resulted in the development of the Asteroid Data Explorer (IAU, 2015b), a tool that presents the data as interactive charts. The information from the Asteroid Data Explorer can be filtered with criteria of interest for the Planetary Defense issue, such as the size of the object or the next close approach. Designed from the beginning as a tool for the general public, it aims at giving its users easy access to data and to manipulate it and share the results via social media. This project comes as a result of the Asteroid Grand Challenge, initiated in 2013 by NASA to “engage people around the world in the effort to find all asteroid threats” (Johnson, 2014). The Asteroid Grand Challenge demonstrates the will of NASA to take a new approach to the NEO threat, reaching out to the public and new organizations to find new ways of using the data and to help develop knowledge by involving amateur astronomers. Appendix D provides an examples of the most important webpages of 2015, regarding Planetary Defense.

Outreach today cannot be effective without using the Internet as a major support. The Internet provides the advantage of accessing large audiences for very low costs. Some rules need to be followed to be effective when considering scientific and technical outreach, as explained in a paper published in the PLOS Computational Biology Journal (Bik et al., 2015). An organization should have a clear strategic idea for short and long-term goals, a consistent campaign, and use storytelling as an effective method of information transfer. The article also stresses the usefulness of recording information on a website’s traffic and social media impact for further analysis, “in order to gauge traffic spikes, content-related trends, and long-term growth in readership”. Following these guidelines becomes crucial when seeking the long-term objective of increasing public awareness on impact threats. Website effectiveness monitoring and analysis needs to contain regular and global surveys of the general public to assess the reach of a campaign.

Our team envisions an online platform providing accurate and up-to-date information to prevent the public from being diverted by false sources, especially in the event of an upcoming close approach. In case a global impact alert level rises significantly, it is of paramount importance to have readily accessible and easy to understand data available to the public that provides accurate information. Any such website should also connect media with scientists involved in the field. While we recommend the investment in such a website,

we did not create one because several similar websites already exist and adding an additional site would cause information to be diffused rather than aggregated.

#### **2.4.2.2 Games**

A few games addressing Planetary Defense have been developed or are under development. The following examples give an overview and show that this area needs more focus.

##### **A. Angry Birds Space**

Angry Birds Space has been downloaded over 100 million times. Rovio Entertainment released a game that sends Angry Birds Space into NASA's next target for future human exploration – asteroids! The collaboration between NASA and Rovio Entertainment through Angry Birds Space is a great opportunity to reach out to millions of gamers and use the fictional universe to point players to real information about asteroids. David S. Weaver, the NASA Associate Administrator for the Office of Communications, praised the collaboration as “a great opportunity to educate, inform, and even inspire players about space exploration, all while playing one of the most popular interactive games ever created.” (Fox, 2014)

##### **B. Kerbal Space Program**

KSP is a space simulation game that enables users to build spaceships and fly missions in a physics-based model. The game's developers worked directly with NASA on the Asteroid Redirect Mission and included a simulation of the mission in the game. Players can import asteroid and comet characteristics into the game and then build and send spacecraft to intercept the object. The game has notably crossed over into the scientific community with scientists and members of the space industry displaying an interest in the game. Additionally, this game is used in educational institutes around the world to teach orbital mechanics to students (KerbalEdu, 2015).

##### **C. World Defenders**

World Defenders is a game created by DiscoveryKids (Discovery Kids, 2015). Within the game the player aims to defend the Earth by simply shooting at incoming asteroids. The biggest flaw of this game is the lack of education concerning asteroids and comets.

##### **D. Killer Asteroids - Impact Earth**

In this game the player can choose the type of NEO, its characteristics, and the impact location. The Killer Asteroids website enables the user to also learn about asteroids, comets, and the hazards they pose to Earth, a feature we want to implement as well (Space Science Institute, 2010).

##### **E. Down to Earth - Crater Impact**

This game enables the user to input parameters of an asteroid on a collision course with the Earth. The object's diameter, trajectory, velocity, density and the target's density are all taken into account. A location is chosen, and after impact the destruction caused is outlined to provide the user with an accurate understanding of the impact's devastation. Crater Impact is a short duration game, and thus fails to keep the user interested (Scott, 2013).

### 2.4.2.3 Conferences, Workshops and Working Groups

Conferences, workshops, and working groups usually attract people already interested in a given topic. The most popular meetings regarding Planetary Defense are the biannual Planetary Defense Conference or more recently at NASA Ames, the First International Workshop on Potentially Hazardous Asteroids Characterization, Atmospheric Entry and Risk Assessment. The Secure World Foundation held a Workshop on International Recommendations for NEO Threat Mitigation and the subject has been discussed during other meetings throughout the past two decades. Due to the relatively limited reach of conferences, workshops, and working groups, we chose to focus on the formerly mentioned areas for outreach development.

### 2.4.3 Proposed Solutions

The Outreach and Education group discussed many potential solutions and deemed the following most feasible for the chosen audience (children ages 6-15).

#### 2.4.3.1 Kerbal Space Program (KSP) Scenario

We will use KSP to simulate asteroid/comet threat scenarios for the project, essentially as a basis for illustration. We plan to add a modification to the program to incorporate asteroids and comets that originate from the Kuiper Belt and the Oort Cloud. A simulation can be run to demonstrate the trajectory of the comet during any scenario desired, such as if a NEO or LPC were to be deflected to avoid collision with the planet.

Orbital parameters are added to replicate the situation of an impending asteroid/comet impact as closely as possible. Inputs of the comet characteristics are taken from calculations made on the Systems Tool Kit (STK). The STK software was used to calculate the trajectory parameters of an asteroid set for a collision course with the Earth. KSP will demonstrate the results of STK as a simulation (Figure 20).



Figure 20: Screenshot from the scenario implemented in KSP

For further development, we will add a spaceship to the mod to show the successful deflection of the object. This ship could make use of a mechanical arm that can connect with the asteroid and push it out of its current trajectory. If possible, a projectile could be directed at the object to perform a kinetic impact.

After successful implementation of the PHO scenario this can be transferred to the global KSP community. Players will be able to learn about the issue and how it may be mitigated. To add to this, the player can replicate the scenario in their own game, or otherwise modify the scenario in their own interests to further promote the issue and expand to the wider community.

### 2.4.3.2 Mobile Game (Cosmic Vengeance)

Our team created a game concept that will be both entertaining and educational. The game will incorporate the Mascot Ash and its counterpart Pho, described in section 2.4.3.3 and Figure 21. In the game, the player launches comets and asteroids towards Earth as part of Pho's army, to cause as much destruction as possible. Earth's defenders, led by Ash, will aim to defend their planet. It is the user's objective to cause as much damage and destruction to Earth as possible. Similar to the combination of birds available in the Angry Birds games, the asteroids and comets in Cosmic Vengeance will become familiar to the player, however the asteroids and comets will be designed to work as real asteroids and comets would. As the player progresses through the game, their ability to pass levels will require them to be familiar with the attributes of asteroids and comets. This will cause the player to learn about different types of asteroids and comets, and the threats each can pose. Each time Earth is struck successfully by an NEO or a LPC, the defense mechanisms of the people on Earth will improve as the defenders adapt, making it more challenging for the player to use the same size and type of object. As the player succeeds in achieving set destruction targets, larger and more destructive asteroids and comets become available to them, enhancing their learning experience. Appendix E contains a more extensive description of the game mechanics.

### 2.4.3.3 Mascot

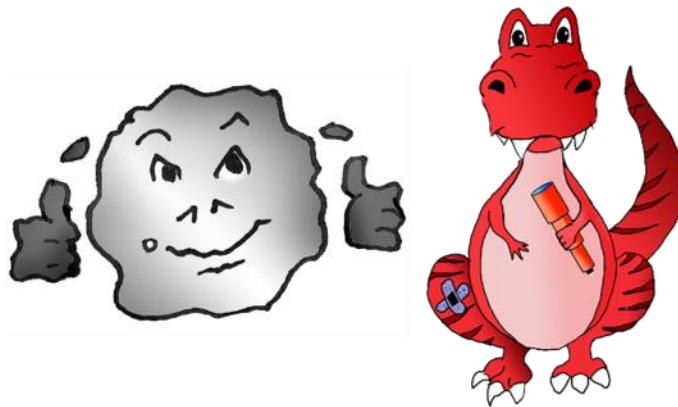


Figure 21: Mascots Pho (left) and Ash (right)

We looked at successful children's public service campaigns as we aim to mimic elements used in them for a Planetary Defense campaign. The most successful and longest running in the US is the Smokey Bear campaign, created and maintained by the US National Forest Service to educate the public on fire safety and preventing wild fires. Smokey Bear was established in 1944 in response to forest fires started by

Japanese balloons floated across the Pacific Ocean. Since its inception, the Smokey Bear campaign has evolved slightly but predominately remained unchanged, aiding brand recognition to its success, since people continue to recognize and relate to the campaign. The campaign created the slogan “Remember, Only You Can Prevent Wildfires”, as another part of the concept for people to relate to.

Smokey Bear’s positive connection with children has led to the success of the fire safety campaign. Children who grew up seeing signs, posters, and TV promotions, of Smokey Bear and his efforts to prevent wildfires have ingrained knowledge of its meaning and importance. Smokey Bear and the National Forest Service encourage children “to write to Smokey Bear expressing their interest in fire prevention”. This has been so successful that Smokey Bear has his own postage zip code in the United States. To accompany Smokey Bear and interest more children, the Junior Forest Ranger program was created to encourage children to take an active role in fire prevention. Involving children also requires the involvement of parents and thus the cycle of life-long learning and participation engrains knowledge and awareness from a young age through adulthood (SDDA, 2012).

We seek to emulate this success and method of outreach by creating a character similar to Smokey Bear that will resonate with youngsters, while simultaneously educating both children and adult alike. Additionally, we aim to partner with scout organizations worldwide to establish a Planetary Defense merit badge that educates young active members of society on the challenges and threats that our world faces from cosmic hazards.

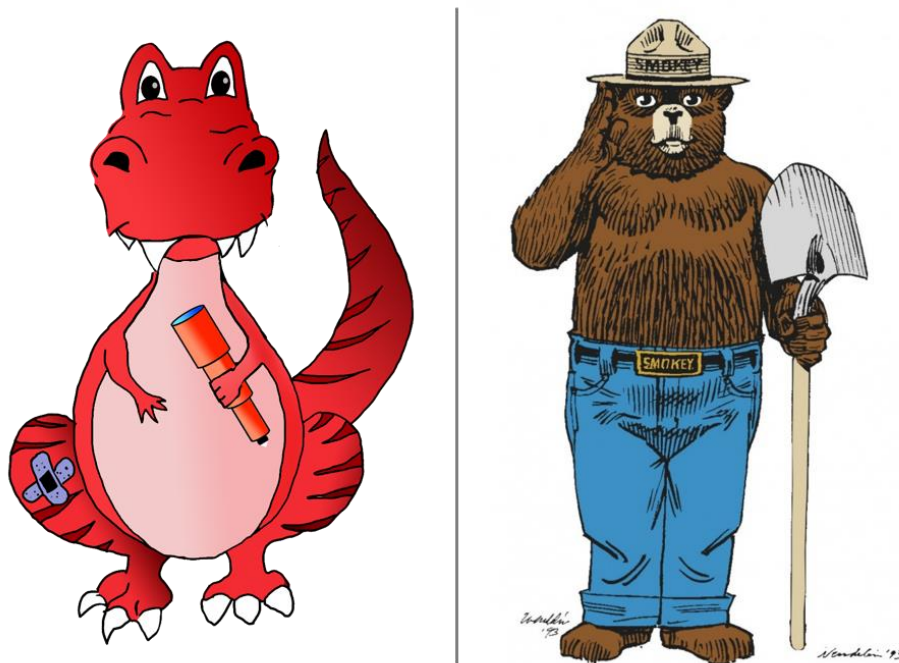


Figure 22: Ash (left) vs Smokey Bear (right) (SDDA, 2012)

Our equivalent to Smokey Bear is Ash the Dinosaur, shown on the left of Figure 22. Ash is modeled following inspection of the enduring aspects of Smokey Bear’s physical appearance, his naming convention, and the relation between his name, his actions, and wildfires. Smokey Bear is always depicted with a ranger hat, blue jeans, and a shovel in hand. Similarly, Ash the Dinosaur will always be depicted with a bandage and a telescope. The bandage represents the trials that he has suffered as a result of previous



impacts. The telescope represents his vigilance and desire to protect Earth from another cataclysmic impact. These symbols will likely remain with Ash the Dinosaur regardless of the situation. Smokey Bear is named for the result of fire and one of its lethal hazards as a reminder of its dangers and seriousness, and he is typically depicted putting out camp fires after campers leave them, protecting other members of the forest after a wildfire, or reminding people to remain vigilant in their fire prevention. Ash is named for a result and lethal hazard of impacts from asteroids and comets, and will be depicted in comparable situations with regard to Planetary Defense, as shown in Figure 23. Ash the Dinosaur will constantly be on the lookout for future threats to life on Earth, he will help defeat the threat, and will encourage children and adults to actively participate in the defense of the planet. Unlike to Smokey Bear, Ash will have a counterpart called Pho, the acronym for Potentially Hazardous Objects, whom he will fight to protect Earth. Finally, Ash will be associated with the hashtag #EyesOnTheSky.



Figure 23: Ash in his environment vs Smokey Bear in his environment (Alaska Centers, 2015)

#### 2.4.3.4 Badge

Scouting organizations are youth programs around the world designed to engage with children and young adults, teach them vital skills, educate them about how the world works, and promote social responsibility. In scouting programs, youngsters work to earn merit badges for learning about and performing a wide variety of tasks. Two of those merit badges in the American version are Astronomy and Space Exploration (Boy Scouts of America, 2015b). The Astronomy Badge is earned when “scouts study how activities in space affect our own planet and bear witness to the wonders of the night sky...” (Boy Scouts of America, 2015a) while the Space Exploration Badge is earned when scouts study the changing nature of exploration and how it contributes to life on earth. Using organizations such as the Scouts is an excellent way of educating active members of society to positively impact the future. We intend to either add an additional merit badge to scouting groups or update the Astronomy Badge with a Planetary Defense knowledge and practical exercise requirement. The addition of Planetary Defense concepts to the scouting organizations around the world will help to promote knowledge of Planetary Defense so that as the scouts come of age and become active members of society they are well informed and can make educated decisions about the topic. Figure 24 shows a suggested badge.





Figure 24: Potential Planetary Defense Badge for Boy Scouts

### 2.4.3.5 Comics

With the outreach and education section mainly focused on the youth, we have started the implementation of comics incorporating Ash and Pho. Comics stand out, provide a meaningful storyline along with visuals, and can be cost effective. Figure 25 is an example of a comic that depicts a young boy sent back in time by Ash to show him the damage from past impacts with Earth. He encourages him to prevent similar destruction in his own future. By including the young boy in the storyline, children are encouraged to connect more to the subject itself, having themselves as main actor to save their home planet.



Figure 25: Comic example

### 2.4.3.6 Video

An additional way to address both youth and the global public is through the use of videos, information surveys, and developing Planetary Defense awareness programs through social media. One such initiative was used during the SSP15 traditional rocket launch, where rockets were named after famous asteroids, such as Apophis, Ceres, and Eros. Over 200 people attended the rocket launch, which provided us with a great opportunity to create public interest and curiosity regarding asteroids and comets. The event was live recorded and the video was made available through Facebook, YouTube and Twitter, providing us with an additional platform to promote the concept of Planetary Defense. To date the videos have received over 700 views.

We conducted surveys to gauge the general public's knowledge regarding the subject of Planetary Defense, and the results are shown in Appendix A. We decided to conduct a general survey covering generic questions regarding NEOs. The survey was designed to gain a perspective on the age of the participants, followed by their occupation, and their knowledge of the topic. Some of the questions focused on what

NEOs entail, and whether or not the general populace can make a distinction between asteroids, comets, planets, moons and satellites. We made this survey available in English, French, German and Spanish. Over 250 people from all across the globe replied, and the results showed a lack of knowledge regarding NEOs and LPCs, and what distinguishes NEOs from other bodies in the Solar System. As a result, we developed an outreach video that introduces the concept of Planetary Defense, defines NEOs and LPCs, explains the importance of Planetary Defense, and makes a case for spreading awareness about Planetary Defense.

We conducted research into the various types of viral videos and how engaging videos are typically structured. Some of the essential components of a successful video include: emotional relatedness, fun factor, promotional branding, uniqueness, public engagement factor, and inspiration. We produced a stop motion video to highlight the issue of NEOs and the threat they pose to Earth. We will publish the video on social media platforms such as Facebook, YouTube, and Twitter, and will use social media best practices and seek support from ISU alumni in promoting the video to reach the widest possible audience.

#### **2.4.3.7 Disaster Management**

Outreach and education should occur prior to an impact, however that does not mean that outreach and education of the public should not be used after an impact has occurred. If an impact is confirmed, it is essential to communicate to the public, manage possible panic, and prepare for evacuation and/or shelter. Depending on the estimated time before the impact, the disaster management can be divided into short, medium, and long-term strategies (Emanuelli et al., 2014).

##### **A. Long-term Strategy**

With enough warning time, regional governments would have the ability to adapt their existing disaster management plans. Many governments already have methods in place for spreading information to their populations regarding disasters. Those systems should be used in the event of an impending impact. Governments and organizations must also use the media to keep the public informed. Every possible means of connecting with a population, including the Internet, television, mobile phones, sirens etc. should be used to prepare the public for an emergency and attempt to prevent the spread of false information. With the impact area being somewhat imprecise for long-term prediction, it is advised that the governments create national points of contact, such that in the case of an emergency an international network is in place to exchange information and support each other in the emergency effort (Emanuelli et al., 2014).

##### **B. Medium-term Strategy**

The importance of transparent communication to keep the general public informed is consistent throughout the entire timeline of an impact scenario. For the medium-term strategy, contingency plans need to be developed. When the threat is not immediate, panic is unlikely. At the early stage it is more important to minimize misinformation by a constant flow of accurate information. Information should be presented in a manner that validates its authenticity by using scientist and other experts. To avoid panic, shocking measurements that are expected to instill fear in the general public should be put into context (Emanuelli et al., 2014).

##### **C. Short-term Strategy**

For the short term strategy it is assumed that the impact area has been confirmed and an imminent threat to a particular region is validated. The focus lies now on the preservation and protection of life within the

impact area. Notification methods should be immediately employed to save the largest number of people possible. The methods of protecting the population will vary from country to country and will be covered in greater detail in the Evacuation and Recovery Section. One simple method of conveying to the global public the threats they will face, is through the use of a color coded scale. Figure 26 shows three different actions that can be taken for short-term strategies: red represents the most endangered regions and implies immediate evacuation, yellow symbolizes smaller, secondary impacts with required measures such as entering bunkers for the time of the impact. For yellow regions, a hazardous destruction is not anticipated, however it is suggested to be at least prepared for evacuation. The blue colored region of the pyramid, the region will most probably face less destructive outcomes. The green colored region is beyond the scope of the short term warning for our project. Preventive actions such as staying inside, keeping doors shut and staying away from windows are recommended. People should continue to pay attention to warning levels as they might change with time. To inform the public of an immediate strike, sirens (outdoor speaker systems), interruptive broadcast, mobile phone notification messages and similar measures need to be generated. Including multiple languages in the warning increases the chance of effectiveness. The messages need to include close to exact impact location, anticipated time and recommended strategy (Emanuelli et al., 2014).



Figure 26: Disaster Management Roadmap

## 2.4.4 Conclusion

Outreach and education are critical to ensuring that the general public and people in positions of authority are informed well enough to make intelligent decisions about Planetary Defense. Without proper outreach and education the general public and decision makers will likely be unable to make effective, well informed choices. Such a situation has the potential to lead to serious, life-changing devastation, or even the extinction of the human race. The READI Project seeks to lay the foundation for life-long learning and sustained outreach that will reshape the general public's knowledge and decision making process with regard to Planetary Defense.

## 2.5 Evacuation and Recovery

### 2.5.1 Introduction

In the event of a failed NEO or LPC deflection, the last line of defense involves developing programs and infrastructure to deal with evacuation and post-impact recovery. Historically, humanity has demonstrated ingenuity and resilience when confronted by natural disasters, and it is reasonable to assume that, with proper planning, humans can survive a NEO or LPC impact as well. We know that it is only a matter of time before Earth is faced with a real cosmic threat, and if deflection efforts fail, human survival will depend on the level of impact-disaster preparedness. This strategy consists of dealing with a threat before impact through evacuation and sheltering, and recovery after the impact. A proper disaster preparedness strategy specific to asteroids and comets can reduce loss of life and facilitate a quicker recovery. Such strategies already exist for a variety of Earth-based natural disasters, and many of these strategies can be tailored to the case of asteroid or comet disaster preparedness.

### 2.5.2 Objectives

The general mind-set when thinking about a NEO or LPC impact is that of an extinction-level event with global consequences. In reality, smaller impacts are much more probable, and can still have large-scale consequences. The scope of this section is to provide an overview of the vast evacuation, damage assessment, and recovery strategies in response to a cosmic impact. We provide a review of the literature, along with recommendations for future action. Our specific objectives include:

- Present innovative technologies to facilitate evacuation/response efforts
- Create an easy-to-follow action-tree to deal with the threat, and include a timeline for the process
- Develop damage assessment and evacuation/recovery plans to respond to an asteroid or comet impact
- Develop an evacuation strategy based on current practices
- Propose contingency modes for plan failures

### 2.5.3 Understanding the Threat

A critical component of impact-disaster preparedness is the understanding of the impact zone, including both the location certainty and damage prediction. The location certainty depends on the quality of the observations and the power of the orbital mechanics models (Hills and Goda, 1999). Only after an impact zone is established can impact preparations and evacuation procedures be implemented. The area of the impact zone depends on the size, type, and trajectory of the impactor as well as on the impact location (Michael et al., 2013). A land impact zone is defined as the area that receives a blast wave of 1psi, which would cause light damage to structures including broken glass (Covey et al., 1994). In contrast, an ocean strike impact zone would include all coastline areas affected by the tsunami that results from the impact (Collins et al., 2005). A water impact is a major concern because most of the world's population lives on the coast. The damage from a cosmic impact comes in a variety of forms, including shockwaves, thermal radiation, debris, and electromagnetic effects (Hills and Goda, 1999). Statistically, the majority of impacts will cause great devastation over a small area. When considering evacuation and recovery strategies, it is

important that governments and organizations consider both the likelihood and severity of an impact across different cosmic threats (Marusek, 2006).

Empirical vulnerability models have been suggested in the past (Norlund et al., 2011) in order to evaluate the number of human casualties in the case of a significant impact. The main assumption underlying these models is that a NEO or LPC impact can be modelled as a combination of disasters such as hurricanes, earthquakes, tsunamis, and large explosions. A cosmic impact is really a “multi-hazard” disaster and as such, requires a combination of different damage assessment and evacuation techniques put together in order to create an appropriate response. Accurate vulnerability models are crucial not only for developing a successful evacuation plan, but also for outlining the possible threat posed by cosmic impacts to decision makers in order to raise sufficient funds and international cooperation (Covey et al., 1994).

Evacuation of even small cities poses numerous challenges. Considerations include: when to inform the public, limits on transportation modes and choke points, border control, sheltering of displaced peoples, the roles of national/local governments, and threat mitigation from secondary damage (Marusek, 2006). Successful evacuation plans must include a mechanism to shelter evacuated people. Literature suggests that large stadium-type structures can offer temporary shelter, as was done in response to Hurricane Katrina (Moynihan, 2009), or in semi-permanent camps such as those used to accommodate refugees (Lawson 2012). Additional logistical and political considerations for evacuation policies will be explored below.

Proper impact disaster preparedness includes taking advanced steps to minimize secondary damage caused by impacts. Such steps include securing oil, gas, and water lines (from sources and in residences) and taking nuclear reactors offline (Michael et al., 2013). Authorities should also encourage residents to prepare their homes by boarding their windows and securing or evacuating valuables (FEMA, 2007). These steps will have the largest impact in the outer regions of the blast radius, away from ground zero. This is evidenced by the Chelyabinsk asteroid in 2013, whose airburst caused an estimated US \$33 million in damages (Michael et al., 2013). Most of these damages came from broken windows and roofs, and could have been minimized with appropriate warning and countermeasures (FEMA, 2006).

The final consideration in an impact disaster preparedness plan is the development of a damage recovery strategy. A quick and thorough recovery plan will mitigate lasting health, social, and economic impacts. Governments can borrow from pre-existing natural disaster plans in developing specific post-impact recovery strategies. Lasting impact effects, which can continue for generations, are an additional consideration for recovery plans. Until such a plan is implemented, we are just as vulnerable as the dinosaurs were.

## 2.5.4 Damage Assessment

Damage assessment is an important element of disaster preparedness. Damage can be predicted using software to run simulations before an impact to have more accurate data about the impact effects. With the results of the simulation, it is possible to prepare an adequate evacuation plan to ensure everybody’s safety. Information about likely damage prior to an impact allows the removal of dangerous materials (e.g., from nuclear reactors) from the impact location to minimize the damage on Earth (Norlund et al., 2011).

### 2.5.4.1 Short and Long-term Impacts

Comets and asteroids can cause significant damages on Earth. When an impactor enters the atmosphere, most of its kinetic energy is dissipated before reaching the ground, but, if the impactor is sufficiently large,



it can cause a ground impact as shown in Figure 27 (Hills and Goda, 1999). The impactor loses a lot of velocity between entry and impact on the ground and it can also break up into several smaller fragments at high altitude. Three scenarios can happen depending on the size, density, and the degree of fragmentation in the atmosphere of the initial object. First, all of the energy can be dissipated at high altitude and no objects will reach the ground. Second, if it is a larger impactor, the energy dissipated in the atmosphere can cause blast waves that will reach the ground and have devastating consequences. Third, some of the kinetic energy is converted in thermal energy: the increase in the temperature can actually vaporize the impactor entirely (Collins et al., 2005). For the largest impactor, blast waves will reach the ground, but there will also be a ground impact including craters, earthquakes, and tsunamis depending of the location of the impact. A big impactor can also cause a lot of dust in the atmosphere and consequently a global darkening for few months (Covey et al., 1994).



Figure 27: (a) Shoemaker Impact Structure, Western Australia; (b) Barringer Crater; (c) Barringer Crater top view; (d) Arizona Meteor Crater aerial view (Source: NASA EO, 2009)

A blast wave is created by the compression of air in the atmosphere due to the passage of an impactor with a high velocity. It is one of the more dangerous effects of an impact, because it can pulverize humans and animals and completely destroy infrastructures (Collins et al., 2005). Effects are comparable to a nuclear explosion, and it is possible to assess the damages by comparing it to existing nuclear bomb test results.

During the impact with the ground, a fireball may be created if the velocity of the impactor at the ground is higher than 15km/s (Collins et al., 2005). A fireball results from the rapid increase in air temperature around the impact location. This thermal radiation can also start a fire in the impact zone. Also, dust and debris will also be ejected, which can cause secondary craters (Reitsema, 2015).

#### 2.5.4.2 Simulation

For this project, the Earth Impact Effects Program developed by R. Marcus, H. J. Melosh, and G. Collins in 2004 (Collins et al., 2005) was used to calculate a variety of effects that can result from a comet impact.



The Earth Impact Effects Program takes a number of parameters as input to determine the effects at a specific distance from the main impact: the diameter and density of the impactor, the impact velocity and angle, and the distance from the impact, as shown in Figure 28. The program gives several different outputs such as the energy, the major global changes, the characteristics of the atmospheric entry, crater dimensions, thermal radiation and seismic effects, characteristics of the ejecta and air blast, and some information about tsunamis if the impact was on water.



Figure 28: Simulation of an asteroid blast showing the area of impact and crater dimensions

In addition, the Near Earth Object Mitigation Support System (NEOMiSS) is a new simulation software system designed by Charlotte Norlund, a Ph.D. student at the University of Southampton. Its main purpose is to inform decision makers on how vulnerable their resources are to potential NEO impacts. The software can provide information on how to evacuate a threatened area before the impact occurs.

NEOMiSS combines the physical effects of the impact with knowledge of strength of buildings and previous natural hazards (Norlund, 2011). It helps to simulate the ability to evacuate the threatened area using behavior-based evacuation models as a measure. All the simulations are based on statistical data, global gridded data, and transportation knowledge of the supposed area of impact collected by Norlund. This tool is useful to respond to an eventual impact and can identify the resilience of areas that may be at risk and areas that need to further develop their transport infrastructure in order to avoid congestions (Norlund, 2011).

### 2.5.4.3 Remote Sensing

Remote sensing is a very useful tool for monitoring and managing natural disasters including cosmic impacts. Remote sensing data can give us information about a variety of factors including the temperature and composition of the air, and maps of the fire area (Ouzounov and Freund, 2004). A limitation of satellite remote sensing specific to monitoring an asteroid or comet impact is the dust that is ejected and suspended in the atmosphere following such an impact. This dust interferes with light detection and ranging (LIDAR) and sonic detection and ranging (SODAR); forms of active remote sensing. Since it takes time for the dust to settle, there is a delay in the ability of remote sensing to be used to gather the data needed to plan a response. However low flying unmanned aircraft could be used for remote sensing to monitor the impact if the dust ceiling is high enough. . An alternative method is synthetic aperture radar (SAR) is an active microwave sensor that can see through dense clouds, and may provide a valuable tool (Joyce et al., 2009). Thermal sensors can also be used to locate wildfires and to map the temperature variations. The spatial

resolution of the thermal sensors is not as good as that of LIDAR or SODAR, but provides valuable data for large areas and long-term monitoring (Nirupama and Simonovic, 2002).

Remote sensing can be used for different applications before and after a disaster. Before an impact, all locations that can be potentially affected by the disaster can be analyzed. For example, it is possible to identify areas of unstable ground or fragile infrastructure and to create high accuracy maps. Buildings and infrastructure fragility depend on many factors, several which can be detected with remote sensing: height, proximity of other structures, and the surrounding environment (Nirupama and Simonovic, 2002).

An impact is a very brief event, so remote sensing cannot play a great role during the impact event itself. After the impact when the dust has settled, remote sensing can be very useful in informing the recovery efforts. The magnitude of damage to buildings, roads, and vegetation, can all be assessed, and the air conditions (e.g. temperature, dust) can be monitored (Van Westen, 2000). Remote sensing can also be used to coordinate the removal of debris, to rebuild infrastructure, and to analyze the regrowth of vegetation and wildlife recovery. It can also be used to analyze the fragility of the ground after the seismic effect, to find locations that are at risk (Joyce et al., 2009). Different satellites (Quickbird, Worldview) are available to obtain these kind of data, and aerial photography is another tool that is very efficient to gather more information. After an impact it would be ideal to constantly monitor the environment around the impact zone, so as to evaluate and characterize the changes (Van Westen, 2000). Agencies can use remote sensing to monitor ongoing recovery efforts to evaluate the effectiveness of particular plans (Joyce et al., 2009). This data can inform the most impactful use of recovery funds. Throughout ongoing recovery efforts, it will be necessary to create new maps which require accurate remote sensing data.

## 2.5.5 Mass Evacuation Strategy

Mass evacuation can refer either to the evacuation of a large number of people or property from an area or to the huge size of the endangered area itself. When we deal with a potential asteroid or comet impact we need to take into consideration both the amount of people and the land area that need to be evacuated in advance. Previous studies have described the physical effects of a NEO or LPC striking land (Marano, Wald and Allen, 2010), in the ocean, or if it explodes in the atmosphere (Brown et al., 2002). These studies have shown that depending on the impactor energy, composition, and the impact location, the physical hazard can be much greater than that of any other known natural disaster (Norlund et al., 2011). Taken together, a cosmic impact may require the largest evacuation effort in human history. However, evacuation may not always be an option as has been noted in the literature.

In this report we discuss currently available massive evacuation strategies and their relevance for our case study. We also cover the unique characteristics of celestial body impact in terms of the required evacuation procedures. Finally, we outline a proposal for a comprehensive massive evacuation. To minimize damage, and maximize survival rates, pre-impact planning must be conducted by both local and federal governments, as well as, at the family level (Marusek, 2006).

### 2.5.5.1 Proposed Evacuation Strategies

This section proposes an outline for a comprehensive massive evacuation plan, focusing on key elements such as relocation of key industries and key assets, managing transportation and communication during the evacuation, relaxation of border controls, mass migration, a national shelter plan, roles and coordination of the various levels of governments, and reliance on individuals and families. The proposed strategy is based

on a review of existing response to natural disasters, mainly focusing on Federal Emergency Management Agency (FEMA) works, as shown in Appendix F.

Due to the large scale of the required evacuation, the main coordinator of these efforts is assumed to be the local government. However, international cooperation is crucial for planning and executing a successful evacuation. An ideal evacuation plan should rely on extensive international agreements, and an international task force that would execute the actual evacuation procedures. The large uncertainties involved with estimating the actual impact zone and associated hazards force the international community to develop a comprehensive operational evacuation strategy. Furthermore, we should also note that a significant asteroid or comet impact is not a singular event. Hence, strong international cooperation will be essential for future threats. The first significant impact encountered in modern history will likely be a lesson for future generation.

As part of an extensive literature review, we identified the critical elements and components of a massive evacuation plan. Figure 29 outlines the main required functions of the evacuation, mostly in terms of the operational execution of the evacuation plan.

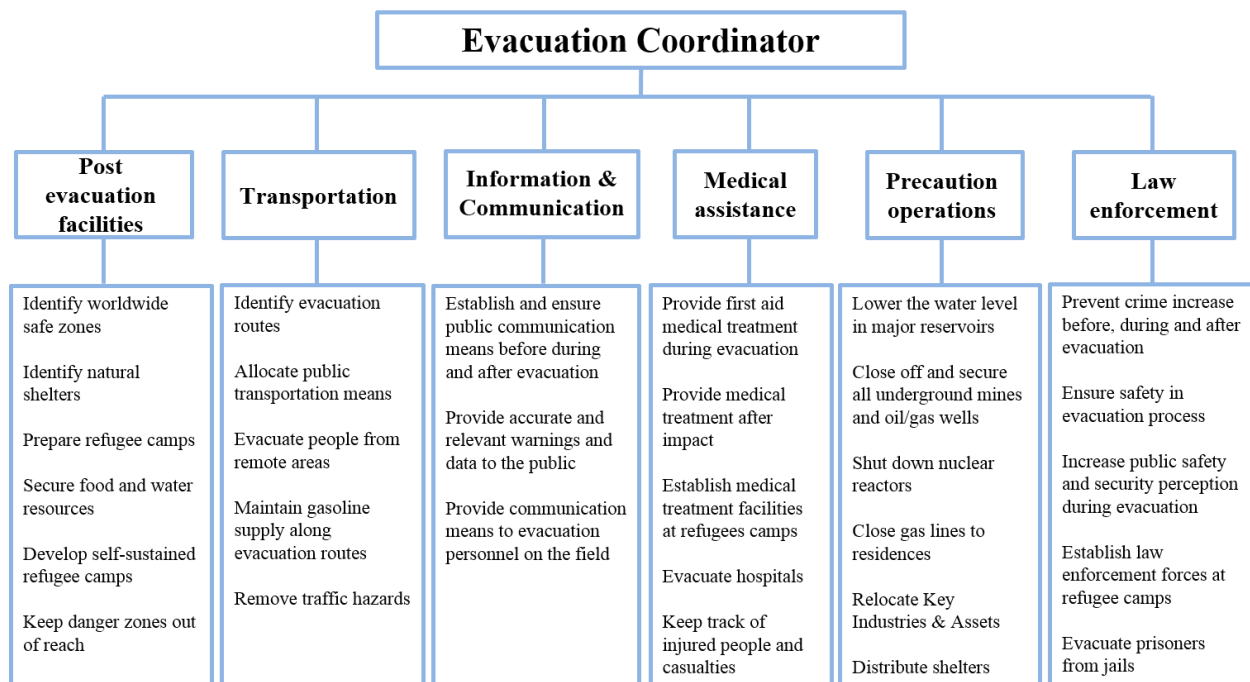


Figure 29: Evacuation Coordination Chart

In addition, time is one of the unique characteristics of cosmic impacts compared to any other known natural hazard. NEOs or LPCs on a collision course with Earth can be detected anywhere from years to minutes before the actual impact. In the following chart, we suggest an operational evacuation timeline for a 2 year warning scenario, shown in Figure 30. A two-year notice is a long time compared to other natural disasters. However we should note that the actual impact location may only be forecasted with sufficient accuracy a few weeks to a few days before the actual impact. In addition, faulty deflection attempts may alter the impact zone greatly, or create multiple smaller impactors instead of one big impactor. We should also note that contingency modes may alter the actual evacuation plan substantially, thus the evacuation plan should

include sufficient time margins as well as a flexible management hierarchy to address different contingency scenarios effectively.

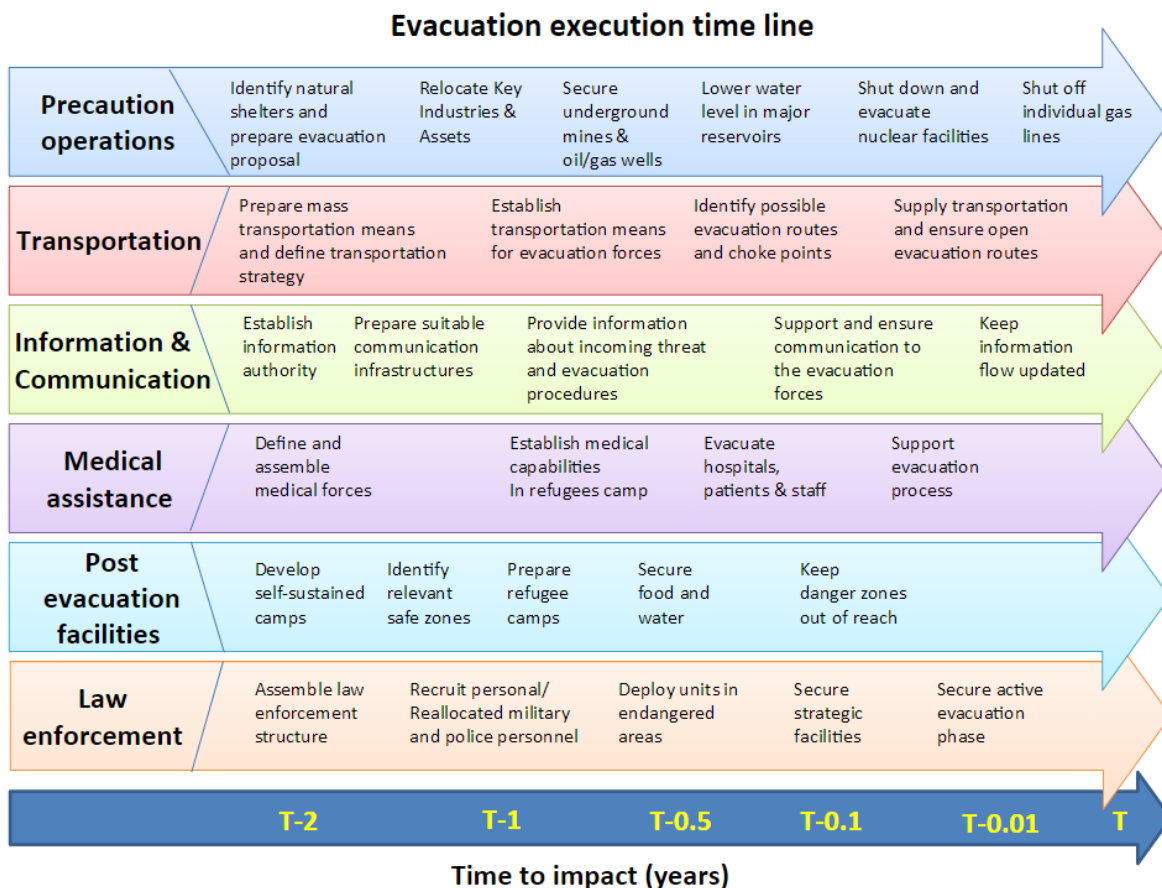


Figure 30: Evacuation execution timeline

## 2.5.6 Shelters

Experts argue that the damage caused by a comet or asteroid impact can be compared to a nuclear explosion of same yield, without the radioactive effects. In the existing civil defense strategies, knowledge of how to design and construct efficient shelters against nuclear threats has expanded significantly and most countries have a large number of these structures. This knowledge can be used to design shelters against the explosion and thermal radiation associated with a potential cosmic impact. Sometimes evacuation may not be the best option due to geological barriers, governmental obstacles, uncertainty in the location of impact, limited time, and inefficient modes of transportation. Therefore, depending on the size of the threat and the predicted location, alternative sheltering options for surviving the effects of the disaster may include natural shelters, pre-existing artificial shelters, or construction of expedient blast shelters (Marusek, 2006). Many countries, especially the Soviet Union and the US developed detailed designs for expedient blast shelters, mostly using common materials, for protection in case of a nuclear threat (FEMA, 2007). In order to have a proper disaster preparedness plan against an impact threat, these designs and other existing ideas should be updated to fit the threat characteristics and then tested and made available for broad usage by any country. The main focus of this section is to review existing shelters, and emphasize the need for strategic expedient or natural shelters.

### 2.5.6.1 Existing Shelters

The analogy between an asteroid or comet impact and a nuclear explosion is very useful because it allows shelter designs to be tested. Among the existing structures that can shield against the blast impacts, we can mention caves, tunnels, and mines. FEMA has been working on compiling a National Underground Mines Inventory for the US and has identified space in caves that can accommodate 4 million people, 2 to 3 million spaces that can be created in tunnels, and up to 100 million areas in existing mines in the US (FEMA, 1983). Yet several factors must be taken considered when proposing to use mines or caves. Many mines are several hundred feet deep and very difficult to access, which means the entrance cannot accommodate a large volume at once. Depending on the size and location of the threat, the infrastructure supporting these structures may be destroyed, so exiting the mines may pose a bigger threat than entering (FEMA, 1983). Another issue that needs to be considered is the accumulation of deadly gases in the mine environment.

These issues should not prevent governments from using caves and mines as a sheltering option in the case of an asteroid or comet impact. A proper contingency plan should address them, as well as additional factors, such as installing or improving permanent lighting, ventilation, access, and sewage, and how to maintain it all during use. Existing technology can help in addressing these factors (FEMA, 2006). Developments in light-emitting diodes (LED) and flashlights technology can contribute to improving the existing lighting in mines. When designing the entrance and exit of the tunnel, directional fans can be placed to improve ventilation.

There are also existing manmade underground shelters such as subways, atomic bomb shelters, underground houses, storm shelters, and root cellars, which can be used in the case of a cosmic impact. Atomic bomb shelters may be the most suitable in this event, due to similarity of the disaster and the lack of need for further reinforcement (Norlund et al., 2011). Fallout shelters are common in countries such as the US, Germany, and the former Soviet Union, as seen in Figure 31, but this type of structure may not be resistant to a big blast caused by an asteroid or comet impact.



Figure 31: (a) Fallout shelter example in Long Island; (b) London underground used as a bomb shelter (Source: Kim, 2014; USH, 2015)

#### A. Expedient Shelters

Expedient shelters fall into the category of self-constructed shelters, which can be used by untrained citizens by simply following written instructions or information provided beforehand. They can be constructed within 48 hours using commonly available tools and materials (Bellew, 2007). These shelters can be a backup plan in case of late detection of the threat and are the fastest means of response by which people



can save themselves and their family. Since their introduction, this kind of shelter has gone through massive changes but the most common types that have been used are shown in Figure 32 (Bellew, 2007).

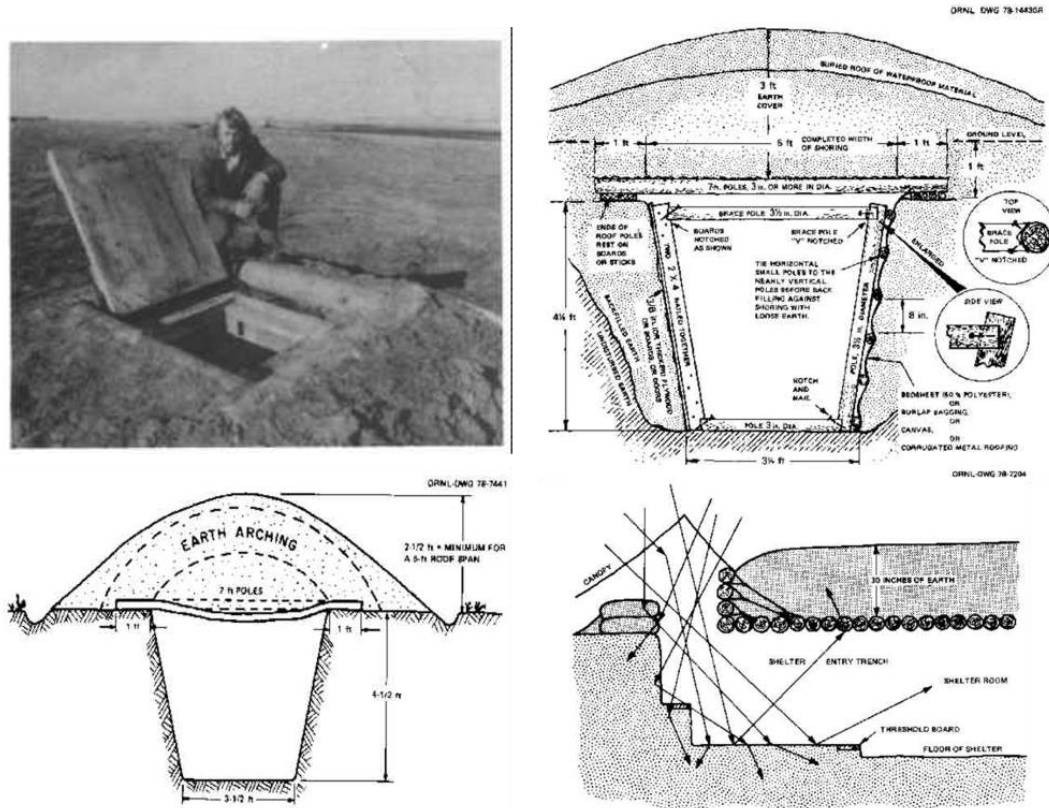


Figure 32: Examples of expedient shelters: (a) blast shelter, (b) expedient blast door, (c) expedient blast shelter shoring, (d) expedient fallout shelter (Source: Bellew, 2007)

Most of the existing designs have been tested to resist an impact of 50psi. In order to achieve this goal based on FEMA requirements (FEMA, 2007), the shelter characteristics should:

- Have a covered entrance
- Be underground
- Have shored sidewalls
- Make use of Earth-arching construction
- Not be constructed in areas of flood risk
- Be flexible to the yield of upcoming loads

## B. Commercial (Modern) Shelters

Some people believe that the world will soon come to a catastrophic end, either from global warming or asteroid impacts. In response to these concerns, some companies have started to design and construct hardened shelters. Most of these companies are located in the USA, and the majority of the projects are at the design proposal stage. One of such companies is Vivos Shelters, which has manufactured underground bunker apartments in Indiana and Nebraska, capable of hosting 50 to 1,000 people (VIVOS, 2015). The main objective of these shelters is to accommodate people for a long time by providing enough storage space for food and other needed facilities, as shown in Figure 33.





Figure 33: Vivos modular shelters example, where each module can support 200 people for 1 year in case of an apocalypse (Source: VIVOS, 2015)

Another company is Hardened Structures, based in Virginia Beach. They are trained engineers who offer their services as shelter designers, programmers, structural engineers, blast engineers, and alternative energy designers. The company has delivered shelters since 1991, most of them also for military use (Hardened Structures, 2015a).

One of their latest projects is the “Genesis” structures series, shown in Figure 34, which was originally developed for military purposes but for which there is high demand as a suitable underground shelter in case of potential disasters and more severe unpredictable threats. They can accommodate a large number of occupants and can be constructed almost anywhere in the world, due to their modular approach allowing flexibility for expansion and short term construction (Hardened Structures, 2015b).

It seems that, regardless of location, any number of structures may be used as shelters. In the case of an asteroid or comet impact, the government may demand the use of such shelters and facilities once the impact site is known to save as many lives as possible.

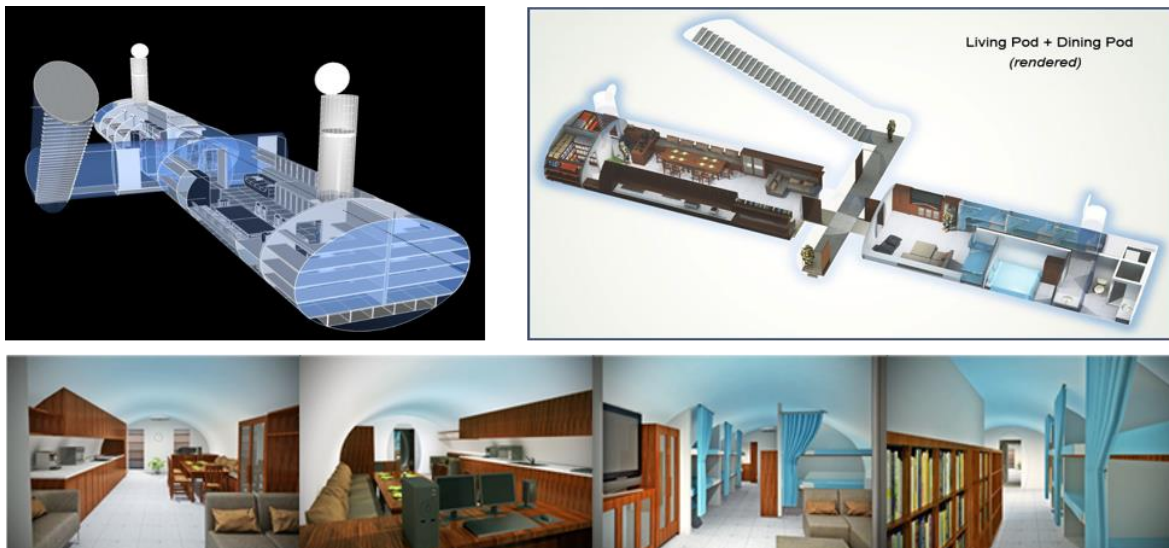


Figure 34: Realistic view of the interior of Genesis Project. The 3D visual shows the flexibility of the module to be expanded further if necessary (Source: Hardenedstructures, 2015b)

### 2.5.6.2 Proposed Strategy for Shelters

A cosmic impact is capable of creating extinction-level damage, so every government should develop proper disaster preparedness plans. Some of the main roles that the government can play are:

- Develop and make accessible a wide range of existing and expedient shelters
- Provide detailed design instructions via the Internet or local offices for expedient shelters
- Conduct tests for each type of shelter to validate its usage, which can also help in deciding on the proper model
- If there is enough time before the impact and evacuation is not the best option, start construction of shelters in unprotected areas
- If needed, use commercial shelters and offer them for free to citizens. The ownership of these shelters can be returned back to the companies after the impact
- Search for other existing types of shelters, such as subways, underground private settlements or fortified buildings

Many existing expedient shelter designs need to be updated to meet modern requirements and technologies. Most of the old versions of shelter design suggest usage of solid wood, but today plywood is stronger and widely used. To contribute to further development of shelter designs, governments and commercial partners should sponsor national design competitions for shelter design, particularly for expedient shelters. The competition should be opened to everyone who wants to contribute and the winning proposal should be built and its effectiveness tested. The results from the competition and the testing can then be incorporated into a report easily accessible by everyone online. The report should include drawings, construction instructions, materials selection, and a list of tools needed to build a successful shelter.

Governments should generate a fair and efficient method of allocating existing shelters to individuals that choose this option and are not able to find safe shelter by themselves in the event of impact. Local authorities should collaborate with their national government to compile an online Shelter Database, where everyone can find information regarding shelters and choose an option. Each local government can also provide assistance for people who cannot access the Internet using the existing infrastructure. Each applicant should be provided with the names, addresses, and numbers of people that will be allocated shelters. This shelter strategy should be extended beyond the case of asteroid or comet impacts to other disasters such as nuclear radiation, flying debris caused by strong winds and nuclear explosions. The allocation of shelters should be done one to two weeks before impact and the shelters should not be able to be reserved.

A sheltering strategy in the case of an asteroid or comet impact includes a proper plan in order to protect as much life as possible, including flora and fauna, so that ecosystems can be rebuilt if needed after an impact. Each government should be responsible for building its own shelters to save and ensure the continuity of life on Earth as we know it. The strategic shelter planning for these elements should not only be related to asteroids or comet impacts, but should also be useful in the case of unpredictable natural disasters, large epidemics, nuclear wars or other artificial catastrophes. Many countries have started the construction of national seed banks. For example, Norway is building a seed vault in Svalbard, which will be able to protect up to 3.5 million different types of seeds. But further efforts should focus on a specific strategy to protect ecosystems. The plan can include construction of a proper shelter and in case of the detection of the threat, governments should start allocating species from zoos, farms, woodlands, wildlife parks, oceans and other

relevant places. The location of the shelter depends on the country, but the best place would be in a desert area between mountains.

Finally, we also propose that governments focus on constructing shelters to protect the knowledge of civilization, including everything from science, technology, history, and literature. If this proposal is feasible at the national level, global collaboration might also be useful to allocate a specific place for all of this knowledge and start making replicas from museums, libraries, websites and national databases. The information contained in the shelter should continue to be updated for as long as possible up to the time of impact.

### **2.5.7 Recovery Strategy**

One of the most important roles of a government is to protect its citizens from harm. In the event that Earth cannot prevent an NEO or LPC impact, further harm should be reduced with appropriate recovery plans. It is critical that these plans be developed in advance, in collaboration with both local municipalities and international aid organizations. The damage from an asteroid or comet can take many forms and last for many years. It is important that recovery plans address these spatial and temporal considerations.

Most of the damage will occur almost immediately in the form of thermal radiation and ground shock, but there remains a risk of tsunami and atmospheric blasts as much as 12 hours following impact (Marusek, 2006). It is after this time that the local population can begin their initial recovery. In parallel with the damage assessment activities introduced above, first steps include repairs to essential infrastructure: communication, transportation, clean water, sanitation, electricity, and medical and food services. If not addressed properly, most of the deaths following an impact could result from starvation and disease rather than direct impact effects (Marusek, 2006). It is only once these essential services are in place that additional recovery efforts can be realized.

The recovery from an asteroid or comet impact can be expected to take years. In the long-term, damage to farming and transportation is expected to impact the availability of food and drinking water. The deposition of dust and heavy metals on the ground would poison Earth and require considerable effort to mitigate. Before the land can be used for farming, this deposited layer would need to be scraped away. Animals grazing on contaminated vegetation may also be hazardous to eat (Marusek, 2006). For these reasons, any long-term recovery plans must account for feeding and watering displaced people in addition to remediating the soil. The government should continue to provision survivors in the impact zone until help and food and water availability is confirmed. If water infrastructure is badly damaged, the government will have to bring water in if possible and supplement this with portable water filtration systems.

### **2.5.8 Conclusion**

Global collaboration is a critical element in Planetary Defense preparedness. A cosmic impact will require massive evacuation and recovery efforts. These efforts will be complex, international and expensive. It is critical that researchers and authorities incorporate NEO and LPC impacts into natural disaster literature and discussions of disaster preparedness. Evacuation efforts require detailed maps of buildings, utilities, transportation, and communications infrastructure before an impact. Impact and evacuation modeling should be utilized to develop realistic first-response and contingency plans. Advancements in remote sensing should be used to optimize modeling efforts.

Following an impact, global collaboration will be necessary to minimize secondary damage. It is important to provide survivors with their basic needs including shelter, food, water, and needed medical assistance. Depending on the severity of the impact, displaced people may need to be permanently relocated, which will require international fundraising and collaboration. Evacuation and shelter strategy can be a very cost-effective mitigation plan in case of an asteroid or comet impact. If planned in advance and coordinated properly with all relevant actors in the matter, the allocation of funding can be more efficient. It can also serve as the last line of defense in case the deflection strategy fails, in order to save lives, prevent massive secondary effects, speed the post-impact recovery, reduce chaos among the general population, and contribute to a successful evacuation.

## Chapter 3. Comet Scenario

### « Shooting a Shooting Star: A Tale of Two Planetary Defense Futures »

#### 3.1 Preface

Comets pose a unique Planetary Defense challenge. They are uncommon, and not as well studied compared to asteroids. Comets typically have nearly parabolic orbits, often having period of hundreds or thousands of years. This makes them unpredictable and transient visitors to our Solar System. When they start reaching the vicinity of the Sun, typically near the orbit of Saturn, their nucleus becomes active and they become bright enough to be observed. Thermal stresses on the comet result in outgassing which can cause orbital perturbations, necessitating increased tracking efforts. Comets are made up of water, dust, and rock, and do not have the same density as asteroids ( $\sim 0.6$  vs.  $2\text{g/cm}^3$ ). They travel with higher velocities ( $\sim 50$  vs.  $20\text{ km/s}$ ) and carry much more energy. Being enigmatic celestial objects, they pose a challenge to Planetary Defense programs.

#### 3.2 Initial Conditions

In the year 2030, humanity was about to face a threat on a scale never before encountered. On 1 January 2030, astronomers spotted a comet coming from the outer edges of the Solar System with an apparent Earth-colliding orbit. Preliminary analysis gave just two years until impact. NASA planetary scientist Dr. Jackelynne Safeguard delivered the news quietly to international representatives and military officials. Dr. Safeguard stated that preliminary analysis suggests that the comet, officially named P/2030A1 (Madhu), does not pose a serious threat to Earth with only a 0.1% chance of impact. Models indicated that a potential Earth impact could occur following perihelion (closest approach to the Sun), during which the orbit and comet structure could be altered substantially. Even at 10% of its current mass, P/2030A1 (Madhu) represented the greatest Planetary Defense challenge humanity had ever faced. The need for continued tracking to update the comet characteristics and threat level was stressed. Dr. Safeguard ended the briefing by making a call for a global effort to study the comet for Planetary Defense and scientific purposes.

##### Comet P/2030A1 (Madhu): At Discovery

Time to impact: 2 years

Threat level: low, 0.1% chance for impact

Size: around 500 m

Rotation period: 11h

The ability of humanity to respond to the P/2030A1 (Madhu) threat in 2030 depended on the advancements in a number of key Planetary Defense fields in the 15 years preceding detection. These fields include Near-Earth Object (NEO) and Long-Period Comet (LPC) detection and tracking, deflection technologies, geopolitics and policy, public awareness and outreach, and evacuation and recovery preparedness. There are many potential futures to the P/2030A1 (Madhu) threat; the following narratives highlight two of them.

#### 3.3 With a Dash of Rocket Science: An Optimistic Scenario

*"I'm a great believer in luck. The harder I work, the more luck I have"* - Thomas Jefferson

*"People who say it cannot be done should not interrupt those who are doing it."* - George Bernard Shaw

### 3.3.1 Pre-detection Phase: 2015-2030 (T0-15)

In the years between 2015 and 2030, governments across the world became increasingly concerned about natural disasters, including NEOs and LPCs, as a result of effective public outreach. Governments, experts, and the media around the world commonly discuss the discoveries of asteroids and comets, and the response strategies if one ever became an impact threat. A significant boost in impact-disaster preparedness came from a shift in governmental risk assessment attitude. A continued expansion of humanity's presence in space reinforced the responsibility of governments to protect their citizens from galactic threats. The global community was aware of low-likelihood, high-severity risks such as cosmic impacts and was primed to deal with such threat.

The acceptance of asteroids and comets as serious threats to human safety started in 2015, with the initiation of many education and outreach campaigns. Children, as the future leaders, scientists, engineers, story tellers, and policy makers were the targets of many outreach campaigns. Through targeting children, parents also became informed. The entertainment industry, in collaboration with government scientists, developed and promoted computer games that incorporated Planetary Defense themes and facts. An example of this was Kerbal Space Program (KPS), a game which was developed in 2011 and quickly became popular. In conjunction with Planetary Defense organizations, comet and asteroid modules were added that incorporate elements of orbital mechanics, cosmic hazards and mitigation strategies, providing a fun, educational product. In conjunction, space agencies around the world became more competent in using social media to reach the public. A new generation of social scientists developed powerful, intercultural viral videos that brought NEOs and LPCs into the global consciousness and dialog. This Planetary Defense enthusiasm led to the creation of two mascots: Ash and Pho. Ash is a lovable and trustworthy T-Rex whose mission is to share his experience about the extinction of his species with the human race. Opposite Ash stands Pho, a fragment of the asteroid that caused the Chicxulub crater, and that is back to visit Earth. Space agencies across the world adopted Ash and Pho into their national level outreach campaigns. Together, these outreach and education initiatives created a culture of Planetary Defense awareness. Globally, people were aware of the threat that cosmic impacts pose, and had a deeper understanding and support for new Planetary Defense technology and policies.

Public opinion helped to drive policy makers to make international arrangements for detection, deflection, evacuation, and recovery support. Countries across the world adopted new policies to facilitate the movement of people, food, water and medical supplies across borders. Such policies primed efficient and streamlined deflection, evacuation and recovery efforts within new international disaster preparedness partnerships. The norm of the Responsibility to Defend Earth (R2DE) was adopted by all countries who possessed the technology and capacity to mitigate a NEO and LPC threat. This led to the creation of the Mitigation Action Group (MAG) within the UN system. The MAG proposal was well received and had fast approval by the United National General Assembly (UNGA) and the United Nations National Security Council (UNSC).

Numerous advancements in space observation were made in the decade and a half leading up to 2030, and the detection of comet P/2030A1 (Madhu). International campaigns to colonize the moon, and to put humans on Mars lead to rapid advancements in observational technology. Public enthusiasm for Outer Space grew to levels above and beyond those in the Apollo era, generating government support and funding. Space agencies, driven by the competition within a rapidly advancing private sector, expanded in size and increased their mandates for exploration. This healthy competition led to an exponential increase in asteroid



and comet detection and tracking systems. Such systems began with the better coordination of international assets after 2015, followed by the adoption of full sky coverage every 24 hours. This was accomplished by the construction of new wide field-of-view telescopes in different locations across the world. Public-private partnerships developed parallel networks of infrared space telescopes, dedicated to NEO and LPC detection, tracking, and characterization that complemented ground-based monitoring capabilities. By 2025 humanity had discovered 90% of asteroids smaller than 50m in diameter, and people around the world generally felt secure onboard spaceship Earth.

The great strides in detection technology seen between 2015 and 2030, were paralleled by similar advancements in asteroid and comet deflection techniques. As the number of confirmed potentially hazardous objects (PHOs) rose, the apparent need for first-line Planetary Defense Program became obvious. Those needs were solidified in 2022, when the Earth was nearly hit by a 320m asteroid that had escaped previous detection. There was much relief when the asteroid was found to have missed a critical keyhole (a region in space where Earth's gravity would alter the orbit of asteroid such that it collides with Earth on subsequent orbits).

The 2022 asteroid delivered a much needed wakeup call, and fast-tracked the development and implementation of many Planetary Defense technologies. As a result of long-term government policies, global collaboration efforts developed a set of synchronized PHO deflection methods jointly called the Synchronized Earth Protection Plan (SEPP). SEPP consisted of a directed energy system (DES), a thermonuclear intercept vehicle, and a ground-based mobile ballistic missile system. Each system was constructed, tested and deployed (launched or put into storage) by 2030 as requested by the UNSC and upon recommendation from the MAG. The DES consisted of two Direct Energy Laser Terminals (DELT) that were deployed to Lagrange points L4 and L5 in 2027. From this location the DELT system could ablate the surface of a target (asteroid or comet) and potentially redirect comets and asteroids at distances as far as 7AU. The thermonuclear system, advertised as the Hypervelocity Comet Intercept Vehicle (HCIV) incorporated a thermonuclear explosive device. The idea would be to launch the HCIV as a contingency defense system if the DELT system failed to deflect the threat. Governments around the world constructed multiple ground-based Mobile Ballistic Protective Domes (MBPD) as the third component of the SEPP. MBPDs did not require the same technical readiness as the DELT and HCIV systems, and represented a redundant, worst-case potential solution. The MBPD used ground based interceptors (surface to air) with conventional warheads that could launch in ballistic flight trajectories. There were many concerns about the dual use nature of the SEPP (i.e. its potential to be used for both civilian and military purposes). It was decided that Switzerland, a historically neutral country would lead the program in collaboration with the United Nations Office for Disaster Risk Reduction (UNISDR). By 2030, humanity integrated a worldwide Planetary Defense Program that experts boasted could handle any NEO threat.

A major outcome of the growing global awareness of asteroids and comets between 2015 and 2030 was a deeper appreciation for how unprepared humanity truly was if a cosmic impact occurred. The UNISDR made impact-disaster preparedness an international priority. Experts and governments agreed that evacuation, damage assessment and recovery planning were critical second lines of defense against NEO and LPC threats. The United Nations paired up with international space and disaster management agencies to study, propose, and implement advancements in these areas. Governments around the world updated transportation and telecommunications infrastructure to incorporate the demands of large-scale evacuations. They expanded roadways to minimize bottlenecks in urban centers, and strengthened communication networks by extending satellite networks and ground based stations. These improvements

were made in parallel with impact modelling that increased the understanding of short and long-term damage.

Fifteen years of impact discussions and disaster preparations created an international environment in 2030 that is both informed about cosmic threats and capable of launching effective mitigation campaigns.

### 3.3.2 Detection Phase: January 2030 (T0)

1 January 2030 started slowly and painfully like most New Year's mornings for Bora and Doron, two young astronomers at the Connolly Observatory for NEO Orbit Localization (COOOL). Soon after arriving at work, they received news that would make their headaches even worse. They received a downlink from the Threat Monitoring Network (TMN) that detected an object with magnitude 21.2 near the ecliptic. Pictures from previous days aligned with the recent observations, showing a change in location of a mysterious object. After some brief analysis, the two astronomers identified the object as a new comet and cataloged it under the name P/2030A1 (Madhu), after the COOOL lead astronomer Dr. Thomas Madhu.

Observations indicated that comet P/2030A1 (Madhu) was approximately 8.15AU (more than 8 times the distance from Earth to the Sun) from the Sun in a highly elliptical trajectory that could result in an Earth impact in two years with a 0.1% probability. Initial calculations revealed the potential impact region was a very narrow and long ellipse that covered almost half the planet, from southeastern Europe to the southern end of Australia. Global communication networks quickly processed and disseminated the warning, and P/2030A1 (Madhu) was given maximum priority. Global networks of space and ground-based telescopes were dedicated to studying P/2030A1 (Madhu) in an attempt to quickly rule out an impact. Infrared telescopes located in Earth-Sun Lagrange points L1 and L2 quickly turned to the comet, yielding an initial size estimate of 470 m to 570 m, and a surface composition of a typical comet (water, methane and carbon dioxide ices). The combined efforts of many astronomers determined P/2030A1 (Madhu) to be a Kuiper Belt object with a long orbital period of 200 years. There were no previous records of a comet with these characteristics, and P/2030A1 (Madhu) was suspected to have been knocked out of its previous orbit by a collision or close pass with another planetary body. In the following weeks, observation systems tracked P/2030A1 (Madhu) and disseminated the data through global reporting systems.

Government and scientific organizations agreed to keep news of the comet's discovery and potential impact confidential until a collision could be confirmed with more certainty, and mitigation campaigns mobilized. Leaders from around the world reviewed the previously established impact-disaster preparedness plans and discussed the next steps in the event impact certainty increased. Planetary Defense officials were concerned, but knew that P/2030A1 (Madhu) is exactly the threat they had been preparing for. The International Asteroid Warning Network (IAWN) was informed about COOOL's identification of P/2030A1 (Madhu) on the same day of its discovery. IAWN relayed the news to the UNSC, who were quick to approve the activation of the MAG.

#### Comet Characteristics

##### Comet orbit:

Semi-major axis: 34.2AU

Period: 200 years

Perihelion: 0.27AU

Aphelion: 68.15AU

Eccentricity: 0.992

Inclination: 174deg. to J2000 ecliptic

### 3.3.3 Tracking and Preparation Phase: February 2030 (T0+1 month)

One month after detection, the number of observations of the comet constrained the orbit enough to raise the impact threat level from a 0.1% chance of impact to 50%. Unpredictable outgassing and the potential for fragmentation limited the impact certainty until the comet passed perihelion. Astronomers and scientists around the world used advanced models of cometary behavior, which incorporated data gained from the series of missions following ESA's Rosetta, to improve impact assumption giving the UNSC the confidence to raise a full alarm.

The members of the UN were informed of the threat, a day before the MAG provided an official report to media outlets. Agencies and political discussion remained transparent with the news media, minimizing the spread of false information and unnecessary panic. In an effort to keep the public informed, respected scientist made regular media appearances and participated in social media campaigns. Comet P/2030A1 (Madhu) was rebranded as Madhusa, a serious but beatable threat. The release of accurate information made the public aware that Madhusa would not be an extinction-level event but, with the impact site unclear, global preparations were necessary. Governments and private organizations produced professional evacuation information videos, translated them into dozens of languages, and through local branches provided complementary training. A well-organized fundraising campaign used the popularity of Ash and Pho to engage the public. Despite the efforts of a few conspiracy theorists and religious fanatics, the public remained calm thanks to the availability and quality of information that the international community of Planetary Defense experts provided. The strengths, past successes, and technology readiness of the SEPP program were shared globally and public opinion remained positive that comet Madhusa would be deflected.

With the impact threat level increased, pre-established NEO and LPC defense action trees were implemented by MAG. Coordinated by IWAN and MAG, and approved by the UNSC, governments and private organizations put Planetary Defense Program into action. These systems included the continued use of tracking stations to refine the orbit necessary for the implementation of deflection strategies. As more data became available, a global community of professionals and amateurs developed highly accurate trajectory and impact models for Madhusa that informed deflection as well as evacuation and recovery efforts. The Mitigation Action Group received the go-ahead to ready the SEPP systems for the first available engagement with Madhusa in four months. Under the direction of the UN International Strategy for Disaster Reduction (UNISDR), international disaster preparedness partners began to coordinate impact preparation and recovery strategies.

### 3.3.4 Deflection Phase 1: June 2030 (T0+5 months)

Five months after the detection of Madhusa, the UNSC approved MAG to start the first SEPP phase, the laser ablation system. This approval was unanimous and nations that were previously involved with the creation of the laser technology waited with trepidation to see the results. The SEPP control center initiated the ablation by activating the two DELT spacecraft, as depicted in Figure 35. The DELT system was designed to collect and convert solar energy using high-efficiency solar arrays (65% efficiency) into a massive phased array of laser beams. Laser ablation would alter the velocity of Madhusa through the ejection of comet mass at the laser target sites. It was a slow process, but was implemented early enough to make a measureable impact over the ensuing months.

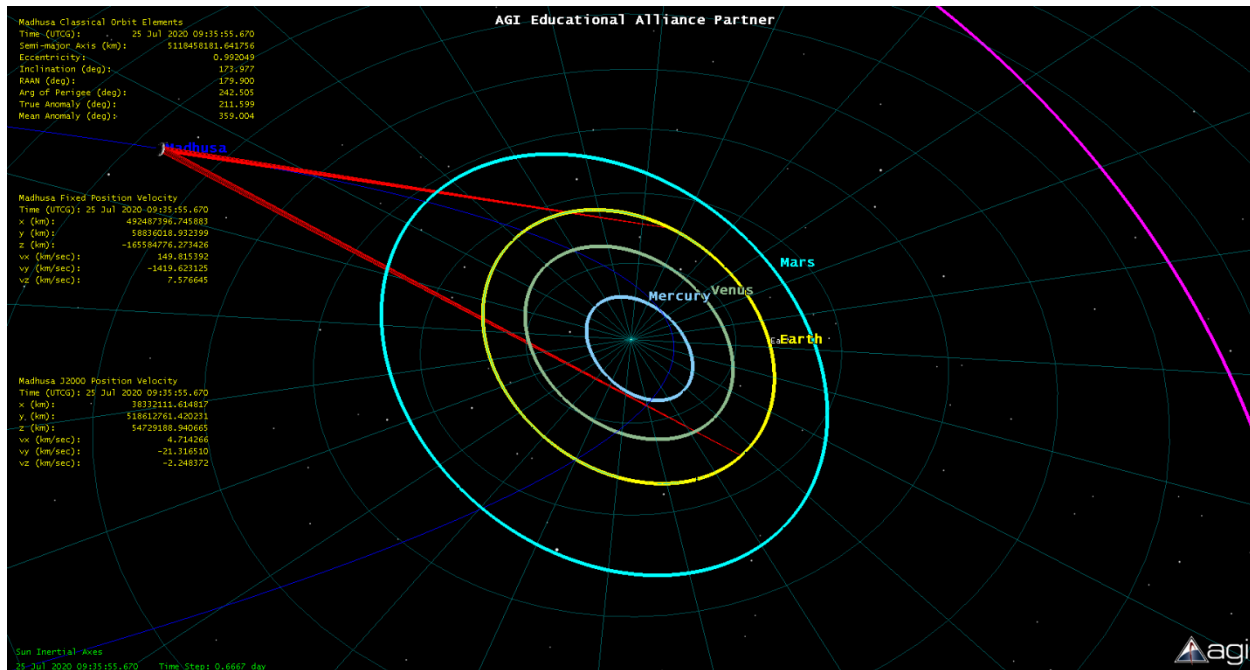


Figure 35: Illustration of the DELT arrays engaging Madhusa

### 3.3.5 Deflection Phase 2: January 2031 (T0+12 months)

Seven months of continuous DELT engagement demonstrated a positive shift in Madhusa's trajectory. The current models suggested that the impact threat had decreased below 10% but, until Madhusa passed perihelion, the new trajectory could not be confirmed. MAG wished to proceed with the HCIV in addition to the DELT engagement, to destroy and redirect as much of the comet as possible. Delivering nuclear devices into orbit presented many geopolitical challenges and the UNSC began discussing the implications of moving forward with the HCIV systems. Objections arose, but ultimately MAG in partnership with the UNSC succeeded in convincing opposing states that the Madhusa threat warranted extreme measures. HCIV was also seen to have tremendous scientific merit, and a team of international researchers joined the HCIV team. The UNSC approved MAG to engage Madhusa with the HCIV. Five HCIV systems were built and positioned in launch sites around the world. The first launch window was seized under the coordination of MAG and the international team launched the 25-megaton (Mt) nuclear devices towards the deflection point near the Sun. The other four HCIV were left grounded until after the results of the first deflection attempt are observed.

#### Impactor

The impactor delivers 238 Gigajoules (940 tons of TNT) of kinetic energy to excavate the crater, which is generated by the combination of the mass of the Impactor (530kg) and its velocity when it impacts (~30km/s) ( $E = \frac{1}{2} m v^2$ ).

The HCIV consisted of two spacecraft. Before the impact 500m away the spacecraft separated for the engagement phase. The first spacecraft to hit was the impactor. Travelling at 30km/s, it delivered kinetic energy to the comet to generate a shallow crater that exposed the hidden subsurface of the comet. The edge of the impactor was manufactured on corundum, mineral with a Mohs hardness equal to nine. This design allowed the spacecraft to reach deeper subsurface layers. The impactor contained the main telemetry, tracking and ranging subsystem of the HCIV systems, and processed the

main set of housekeeping data of the mission. Minor trajectory and attitude corrections were provided by a secondary propulsion subsystem (liquid-propulsion thrusters).

The thermonuclear device (TND) spacecraft included the main propulsion subsystem. Its main payload consisted of a three-stage (fission-fusion-fission) jacket fissioning thermonuclear payload. The TND would follow behind the impactor and detonate within the crater created by it. The concave surface area increased the absorption of the released energy and maximized the ground shock coupling and disruption of the target. Each TND was capable of delivering a 25Mt blast, with a mass of approximately 4,000kg.

#### TND

The fusion stage is created by highly efficient and stable combination of deuterium and tritium ( $d + t \rightarrow He^4 + n + 17.59MeV$ ). The fission stages use low fissionable isotopes of uranium-242 concentrated and highly stabilized within a magnetized container.

These isotopes provide a high kinetic energy for the fission fragments, increasing the internal temperature for the fusion stage.

The media constantly covered the DELT's progress and news coverage of the launch praised the apparent success of the DELT system and the launch of the HCIV, both of which were received very well by the public. Government and private organizations remained prepared for failure of both deflection systems and continued to explore and prepare contingency plans. UNISDR and local organizations discussed coastal evacuation plans. Deployable shelters placed inland were seen as an attractive temporary solution to accommodate displaced peoples. Such shelters were previously used in supporting hurricane evacuations as well as war zone refugee camps. The global community adopted a policy of mandatory evacuation which was shared with the public. The mobilization of evacuation support teams was held off until outcomes of the deflection mission were clear. The uncertainty of an impact and its location limited any growing panic, but comet Madhusa and the deflection mission continued to dominate the news.

### 3.3.6 Deflection Phase 3: October 2031 (T0+21 months)

Three months before the initial Earth-comet collision date, the HCIVs successfully engaged Madhusa. Observations confirmed that the combination of DELT and HCIV deflected Madhusa as planned. The probability of impact was reduced to about 0.001% but there was still no way to confirm the full deflection until after the comet's perihelion passage. It remained possible for Madhusa to break up, directing new fragments towards Earth. The space assets in the Lagrange points would be able to reacquire Madhusa shortly after perihelion, providing the much expected confirmation.

The UNSC began discussing under which conditions the regional ballistic domes should be used, in case any fragments of the comet remained. They agreed that the risk was acceptable and MAG was given authorization to arm regional ballistic domes for a last effort to disrupt any Madhusa fragments that threatened the planet.

News of the ongoing successes of the SEPP missions remained in the headlines around the globe. The progress of the deflection mission was monitored carefully by UNISDR, and a large scale evacuation seemed extremely unlikely. Disaster response infrastructure was kept on high alert until the comet passed.



### 3.3.7 Impact and Recovery Phase: January 2032 (T0+24 months)

The infrared space telescopes in the Lagrange points were able to observe Madhusa shortly after its perihelion passage. The TMN confirmed that the comet had been deflected successfully, and turned from a deadly threat into a beautiful astronomical show as its remnants flew by Earth inside the Moon's orbit. News of a successful deflection was met with global excitement and pride. The Madhusa mitigation mission was a true global collaboration from detection to recovery planning. Across the world, humans felt increasingly like global citizens. This momentum was leveraged into movies, novels and numerous academic papers highlighting the success of the Madhusa mitigation mission. The interdisciplinary, international, and intercultural nature of the mission became a model for future global collaborations.

The Madhusa mission had been an overwhelming international success. Through unprecedented global collaboration, long-term planning, and risk analysis the Madhusa mission united the world in a common victory. In the weeks following the Madhusa meteor shower, governments began compiling the lessons learned to improve the systems that saved thousands of lives. The scale of the Madhusa mission had been enormous and expensive. Extensive fundraising campaigns led to a revolution in the impact disaster preparedness. The global community emerged from the Madhusa incident more unified, sure of humanity's long-term survival, and much better prepared to face the challenges of the future. The DELT lasers were put into hibernation, awaiting the next PHO that strays too close to Earth.

## 3.4 Fast Rocks and Hard Knocks: A Pessimistic Scenario

*"The world is a dangerous place to live; not because of the people who are evil, but because of the people who don't do anything about it."* - Albert Einstein

*"The best time to plant a tree was twenty years ago, the second best time is today."* - Ancient Chinese Proverb

### 3.4.1 Pre-detection Phase: 2015-2030 (T0-15)

In the years between 2015 and 2030, little political, scientific, or public attention was given to asteroids and comets. By early 2016, the general public had largely forgotten about the success of the Rosetta mission, and the concurrent cancellation of NASA's Asteroid Redirect Mission marked the end of future NEO exploration efforts. Asteroid mining companies deployed some private infrared telescopes to detect asteroids, but very little effort was placed on detecting comets. Organizations maintained ground based telescopes but the construction of new observatories stopped following the Five Hundred Meter Aperture Spherical Telescope (FAST) in Pingtang County, China in 2016.

Governments around the world became increasingly short-sighted. Political uncertainty created an unwillingness to address low-probability, high-risk threats such as cosmic impacts. International organizations remained interested in Planetary Defense, but were slowed by reduced funding and political support. The establishment of IAWN and SMPAG in 2013 was a step in the right direction, however the UN COPUOS was initially unsuccessful in getting approval to form a MAG to oversee NEO deflection and preparedness initiatives according to recommendations from the UNGA. The UNGA voted against the formation of MAG, citing concerns about decision making and accountability.



The vulnerability of Earth to PHOs became apparent in 2022 when a 320m asteroid was detected and found to have a high probability of hitting Earth within 4 years. There was no existing technology to deflect the asteroid, and the UNSC took a wait-and-see approach, while debating the use of nuclear technology. Scientists and engineers were dismayed by the lack of urgency from the global community. With great luck, the asteroid missed a critical keyhole and the probability of impact in 2026 dropped to zero. Rather than motivating the adoption of Planetary Defense initiatives, the miss just strengthened the public and political apathy about the threat of comets and asteroids.

The support and funding environment for Planetary Defense between 2015 and 2030 was sparse. A few organizations supported small research programs, but were restricted to publishing white paper reports without any technology demonstrations. Nuclear devices remained controversial, and advances in this field were non-existent. Without the validation from technological demonstrations in space to determine readiness, the technology readiness level (TRL) remained low.

In the 15 years leading up to 2030, few Planetary Defense outreach and education initiatives took hold. As a consequence, asteroids, comets, and Planetary Defense were not integrated into the global culture. A couple of developments such as information videos and mobile games attracted niche audiences but failed to gather any significant impact on public opinion. National space agencies quickly abandoned the global Planetary Defense mascots Ash the dinosaur and Pho the asteroid. In the area of Planetary Defense, 2030 is remarkably similar to 2015, and without advanced notice humanity had a limited ability to respond to any serious NEO or LPC threat.

### 3.4.2 Detection Phase: January 2030 (T0)

On New Year's Day 2030, Marianne, a keen first-year PhD student was reviewing a stream of images from the soon to be retired James Webb Space Telescope at the request of her advisor Dr. Thomas Madhu. She found an unusual spot of light in one of the images. It appeared to be a new object, with magnitude 21.2, and its slow relative motion indicated that it was far away in the outer Solar System. These images appeared to align with a couple of earlier observations but were not enough to determine an orbit for the mysterious object. After some days of pushing Dr. Madhu for more dedicated observing time, Marianne managed to gather enough observations to characterize to object. The comet was officially named P/2030A1 (Madhu), but Marianne, having a dark sense of humor, starts to tweet the discovery as comet Madhusa.

Madhusa first appeared around 8.15AU from the Sun in a highly elliptical trajectory. Preliminary calculations suggested that an Earth impact could be possible in 2 years with a probability of 0.1%. Marianne and Dr. Madhu identified the potential impact region as a very narrow but long ellipse that covered almost half the planet, from southeastern Europe to the southern end of Australia, however this was high speculative interpretation. The relatively high chance of an Earth collision compared to the other usual alerts alarmed Marianne and Dr. Madhu, but they understood that it is too complicated to predict a comet's orbit until after it passes the closest approach to the Sun, the perihelion. In previous observations, threat levels had decreased as the orbit was determined with higher precision, and the astronomers did not feel a formal warning was justified.

After hearing some buzz on social media outlets in response to Marianne's tweets, IAWN contacted Dr. Madhu for more information. IAWN, with nothing better to do, decided that Madhusa posed a reasonable threat and called for a discussion between the international space agencies regarding the current capabilities of putting a deflection campaign together. The detection of comet Madhusa was met with skepticism and

politicians were hesitant to accept that it posed any real risk. In the absence of a tested and accepted deflection systems, very little work was done to prepare a deflection mission in the first weeks following detection.

### 3.4.3 Tracking Phase 1: February 2030 (T+1 month)

One month after detection, there remained limited data about the Madhusa threat. Madhusa was suspected to be an object from the Kuiper Belt, with a long orbital period of 200 years. A few follow up sightings yielded little new information but the chance of impact remained around 1%. The size of the nucleus was constrained to between 250m and 570m. With limited preexisting data on comets, astronomers found it difficult to estimate the comet's albedo. A better estimation of the comet size would not be possible until it got closer to the Sun and more telescopes could observe it.

News about the Madhusa threat escalated slowly, gaining the most attention in dooms-day cults who saw the comet as a sign that humanity was about to end. News outlets, particularly inflammatory ones, began interviewing amateur astronomers to generate high viewer numbers with sensationalized stories. Notably, Weasel News started a daily segment on comet Madhusa that gained international attraction, and directly contributed to a growing fear among the public. Politicians were suspiciously vague about the threat, which contributed to the growing public unrest. Conspiracy theories started to spread, making it difficult to discriminate fact from fiction.

### 3.4.4 Tracking Phase 2: April 2030 (T+3 months)

It took three months to acquire enough observations of Madhusa to confirm everyone's fears. They reported a 50% probability for an Earth impact in just under two years. The new data confined the impact site to a several-thousand-kilometer long, narrow ellipse across the Indian Ocean. Astronomers would not be able to narrow the impact site further until after Madhusa crossed perihelion due to outgassing and the potential for fragmentation. Very little was known about these phenomena making all the predictions very speculative.

The increased threat level caught many policy makers off guard. The UNGA convened under the direction of the UN Secretary General (UNSG) and UNSC. The UNGA requested that all nations start sharing all information about observation and deflection technology. Planetary Defense experts were concerned that it was too little too late for the launch of an effective mitigation program. All nations were called to develop emergency evacuation plans for their territory and to prepare for a potential influx of refugees from neighboring nations. Without pre-existing international disaster preparedness collaborations, it was not clear how evacuation and recovery planning should proceed. Many governments, especially those outside the impact trajectory, remained foolishly optimistic that new data would decrease the threat level. Global collaborations were never formally established, which stalled preparations.

NASA official Dr. Jackelynne Safeguard, delivered an official statement about the rise in threat level. She emphasized that the very best in the world were working on a solution and for everyone to review their local emergency response procedures and to remain calm. The lack of transparency in handling the Madhusa threat had decreased trust in the competency of MAG and the UNSC in handling the threat. The lack of a coordinated deflection plan contributed to growing panic around the world.

### 3.4.5 Deflection Phase 1: January 2031 (T+12 months)

In the year following detection, the world went through a roller coaster of denial, acceptance, hope, and fear. With only a year before the suspected impact, the ability of humanity to mount a response remained uncertain. The UNSC made a call for a global deflection plan but there was disagreement among nations on how to best respond. No norms existed to support a global collaboration to defend Earth, and a high degree of mistrust and a low degree of transparency existed across nations.

As news of the Madhusa comet threat spread internationally, citizens became increasingly worried about their safety. The lack of political leadership led to public unrest and the formation of public advocacy groups. These groups started demanding more information about what had been and would be done about the comet. National space agencies started running numerous damage assessment simulations without taking any concrete steps. The available data on Madhusa remained limited, and the global community failed to reach a consensus on how evacuation and recovery efforts should proceed. Individual governments began reviewing preexisting evacuation policies, trying to apply them to different impact scenarios.

The United States and India, frustrated with the slow pace of the UNSC to respond, decided to collaborate on a deflection plan without international approval. The Indian government created an ambitious plan to upgrade its Geosynchronous Satellite Launch Vehicle (GSLV) launcher through its national space agency Indian Space Research Organization (ISRO) to carry an American thermonuclear payload. The program was kept secret, and with the help of NASA an updated version of the GSLV Mk III was developed in only six months, but missed two of the three launch opportunities.

### 3.4.6 Deflection Phase 2: July 2031 (T+18 months)

After 6 months of development, the USA and India decided to take bilateral action. Their strategy included launching an untested nuclear device, relying on the norm of self-preservation in an extensive interpretation of Article 51 from the UN Charter. UNSC strongly condemned the actions while requesting that the USA and India share their plans and future steps with the committee.

In July 2031, the GSLV Mk III carrying the 5MT thermonuclear device was successfully launched from Satish Dhawan Space Centre, India. The USA and India launched the 3.3-ton MK39-II nuclear warhead with some fear of international backlash, inspiring global anger and mistrust. The UNSC requested that all other nations show restraint and not react to their actions. The spacecraft was sent on a direct heliocentric trajectory to intercept the incoming comet at its closest passage to the Sun. The mission was jointly monitored by the American and Indian space agencies, and the launch and initial trajectory went according to plan.

As the payload approached its final phase, the tracking system aboard the Indian interplanetary vehicle struggled to maintain its course. After 10 days the interceptor made its final automatic calculations and concluded that it may miss the 500m target by a short distance. Minutes before the hypervelocity flyby the backup timer was given full authority over detonation. The payload detonated near the target but, due to the high relative closing velocity (nearly 80 km/s), the timing of the explosion was inaccurate, and the ablation effects were less than predicted. The warhead detonated a few kilometers away from the comet. The shower of neutrons and gamma rays still penetrated up to 20cm through the dirty ice, which vaporized a thin layer around the exposed face. The resulting vaporization effect, coupled with loss of mass, imparted a small thrust on the comet. At the time of the explosion, there was no line of sight from Earth or any

observation satellites. The outcome of the American-Indian launch would only be known once Madhusa began to turn back towards Earth.

### 3.4.7 Deflection Phase 3: October 2031 (T+21 months)

After comet Madhusa passed perihelion, observations confirmed that the size of the nucleus had been somewhat reduced by the heat of the Sun. The comet was estimated to now be around 400m in diameter. Continuous tracking confirmed the worst: the deflection attempt had failed completely to redirect Madhusa away from an Earth impact trajectory. Models gave less than a 1% chance of a miss. Additionally, the explosion had moved the impact site from the Indian Ocean to a 1000km long region in central Europe, crossing the Franco-German border. France and Germany were now faced with a direct impact, an estimated 4gigatons of energy, 80 times more than the biggest nuclear bomb ever detonated. Neither France, Germany, nor the international community were prepared for such an impact. The general public reacted negatively to the new information, and blamed the Indians and Americans for what appeared to be an attack on their economic power. Newspapers started smear campaigns, and American and Indian expatriates living in the European Union suffered the public backlash.

Two weeks before impact, astronomers determined with a high level of accuracy that the affected area was constrained to a 100km long ellipse centered near Strasbourg, France, containing a population of 220,000 people. In a last desperate defensive measure to deflect the comet, the UNSC approved Europe's decision to use existing ballistic missile defense technology to attempt to disrupt the comet before it entered Earth's atmosphere. UNSC called for collaborative preparation in the predicted area of impact for international humanitarian assistance and asked developed nations to graciously accept refugees. The UNSC also approved all available measures to help all nations that would be impacted by comet.

Evacuation and impact preparations were inhibited by a widespread lack of government trust following the secretive and failed deflection campaign championed by the USA and India. France and Germany increased their military activity in an attempt to maintain order and prepare for evacuations activities. Military forces were deployed to eastern France and western Germany to facilitate mandatory evacuations. The evacuation preparations had not been released publicly and people began to flee the impact zone, leaving transportation overwhelmed, and slowing the economy. African, American, and Asian countries were concerned with regulating the influx of displaced people and strengthened their own borders, limiting admittance of refugees. In the last week prior to impact, astronomers confirmed that the comet had several small fragments following the main 400m body, which would increase the area affected by the impact.

### 3.4.8 Impact and Recovery Phase: January 2032 (T+24 months)

As the first fragments entered the upper atmosphere, they began to ablate, illuminating the dark, early morning sky over France and Germany. The fragments quickly became brighter and hotter than the surface of the Sun. Shockwaves produced by the hypersonic entry broke the meteor pieces apart, spreading the devastation across the sky. Within seconds, the fragments began to strike Earth. Fragments spread from the western edge of Germany through France. The lack of time before the impact prevented any ballistic missile defense to be prepared, and the main body of Madhusa reached the atmosphere intact. A single large fragment impacted Strasbourg sending ground shockwaves over an area of more than 100km and creating a seismic event measuring 6.5 on the Richter scale. This fragment created a crater over 3km across, ejecting debris into the atmosphere. After the impact, air shockwaves smashed into the impact zone causing massive

damage, worse than the largest nuclear explosion. An area measuring a dozen kilometers in diameter was completely devastated. No structures within this region survived as Madhusa's catastrophic effects completely demolishing the area. Vegetation was ravaged as forests were flattened and left burning. At 20km from the impact site, thermal radiation was intense enough to kill all the remaining people, animals, and vegetation. The shockwave also caused significant ear damage out to a distance of 40km from the impact site. At a distance of about 100km from the main impact, the shockwave caused windows to shatter. The whole event only lasted five to six minutes, but the loss of life was staggeting and the long-term environmental and economic consequences of Madhusa would last for generations.

The majority of the population was evacuated or fled prior to the impact, however there were a few who decided to stay, or could not be evacuated. Those that remained within the impact zone were killed almost instantly, while injuries and death occurred out to 100km. People were not told to keep away from windows, and as a result many were injured from shattering glass. The evacuation was not monitored or tracked and the number of casualties was not immediately clear. First responders were slow to mobilize, and the death toll continued to rise in the hours and days following the impact. Global support and emergency infrastructure were insufficient to support all the refugees. There was limited capacity to deliver food and water to the displaced people and stores were rapidly consumed. As the situation grew more and more dire, the death toll rapidly increased, and many of the deaths were due to lack of preparation in addition to the impact itself.

In the months following the impact, the world's atmosphere remained clouded with dust. As the dust settled, remote sensing data became available to assess the damage. The impact zone was completely devastated and required a monumental effort to rebuild. International aid organizations, acknowledging their failure, raised huge amounts in support of Madhusa's victims. As a result of the failure of governments and private organizations to develop appropriate recovery plans and the misappropriation of funds, the cost of recovery skyrocketed and the efforts took years longer than expected. The regrets of indecision began to set in as governments started blaming each other for complacency and lack of preparation. It would take decades for nations and the global economy to return to its pre-Madhusa state.

### Impact Characteristics

#### At atmosphere entry (worst case):

Relative velocity: 36km/s

Impact angle: 45deg

#### Location:

- Large fragments centered on Strasbourg, France
- Smaller fragments scattered in an areas 100km around Strasbourg, including areas of France and Germany

Velocity at impact: 19km/s

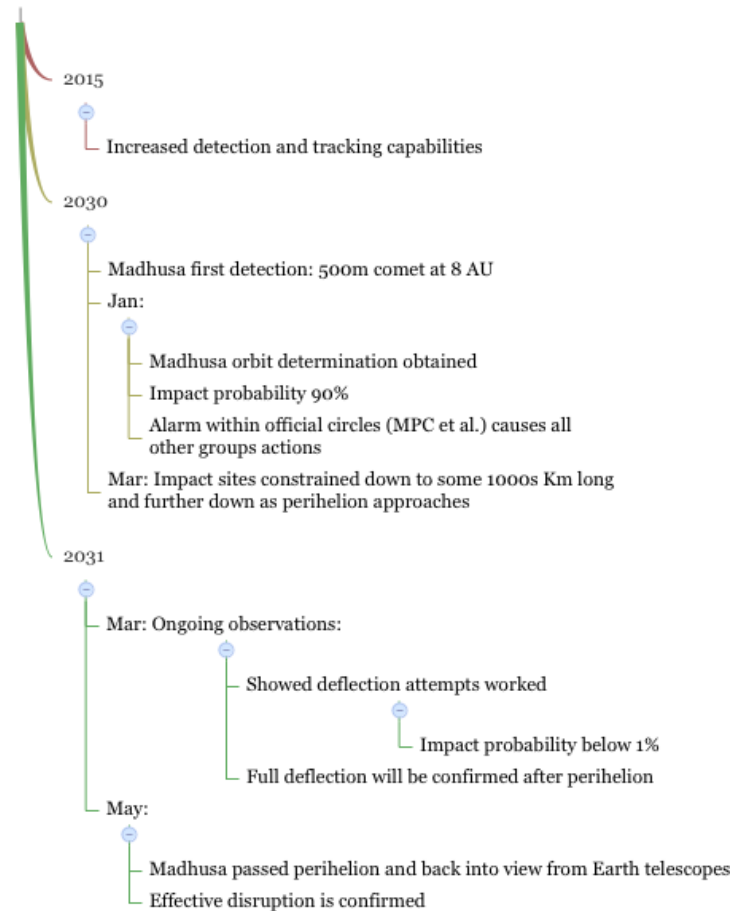
Impact energy: 885Mt

#### Main crater:

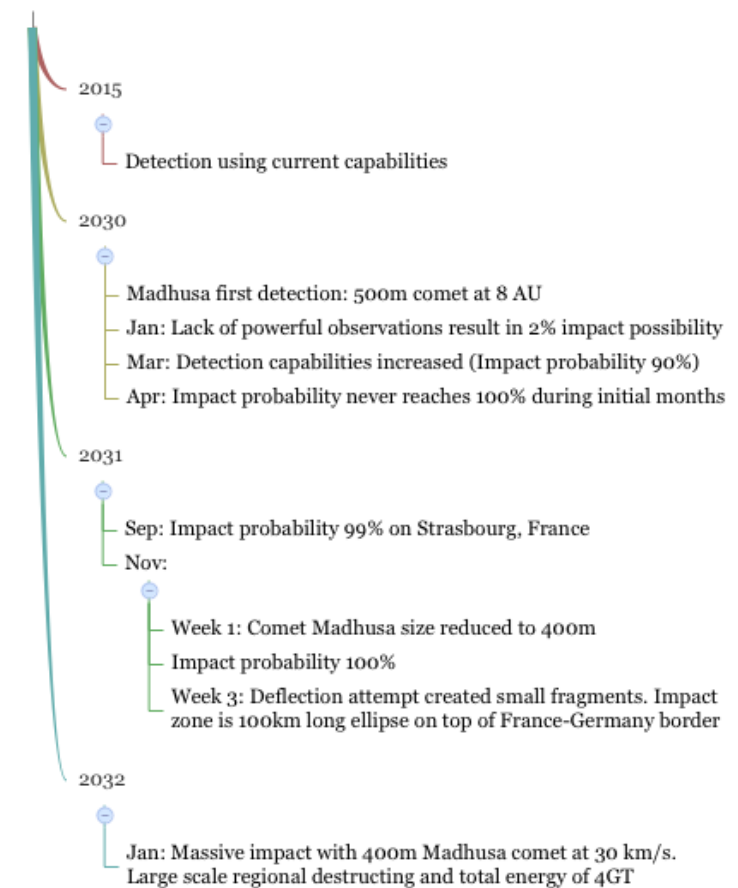
- Diameter is 3.7km
  - Depth is 440m
- Richter scale magnitude: 6.5

## 3.5 Timelines

### Optimistic Scenario: Detection

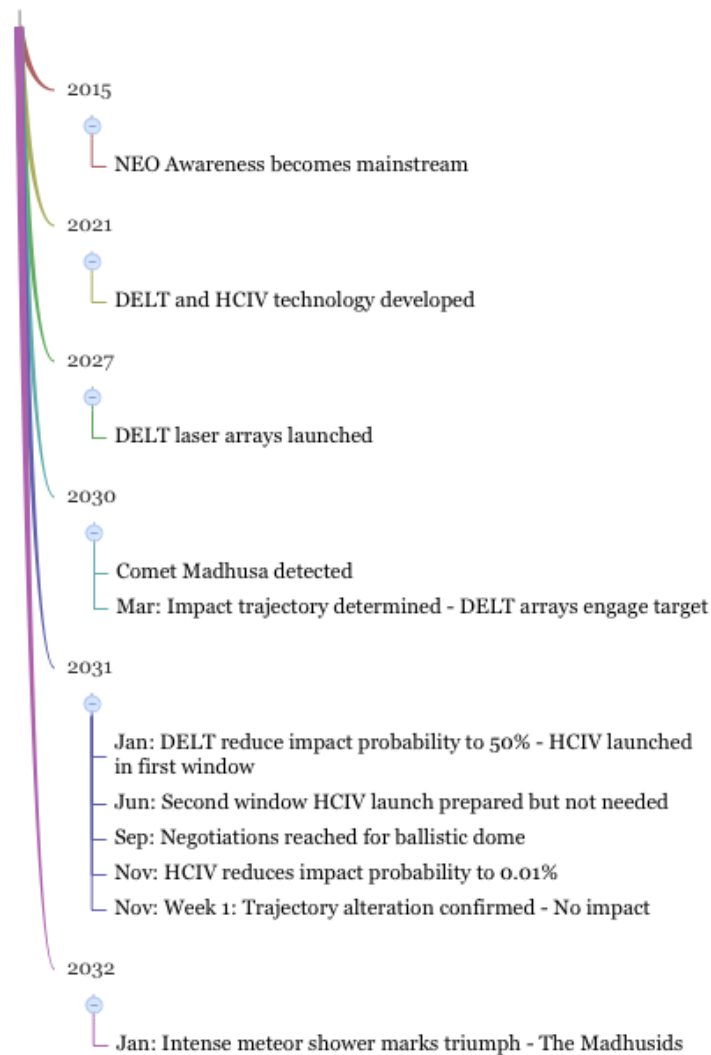


### Pessimistic Scenario: Detection

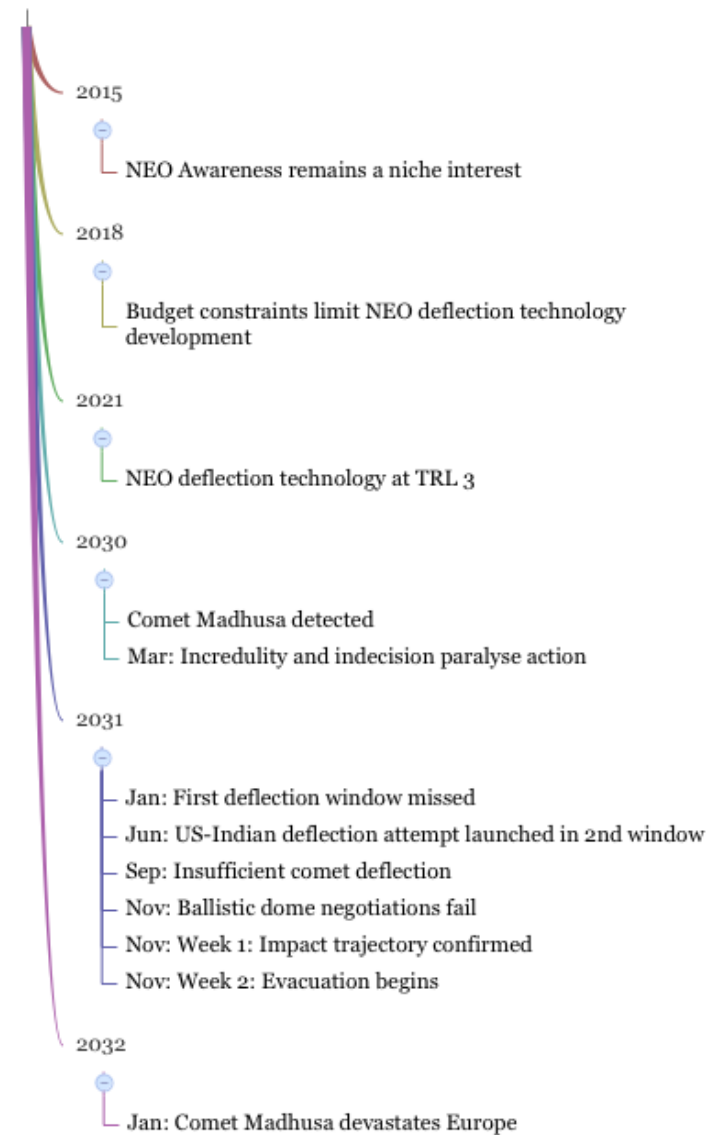




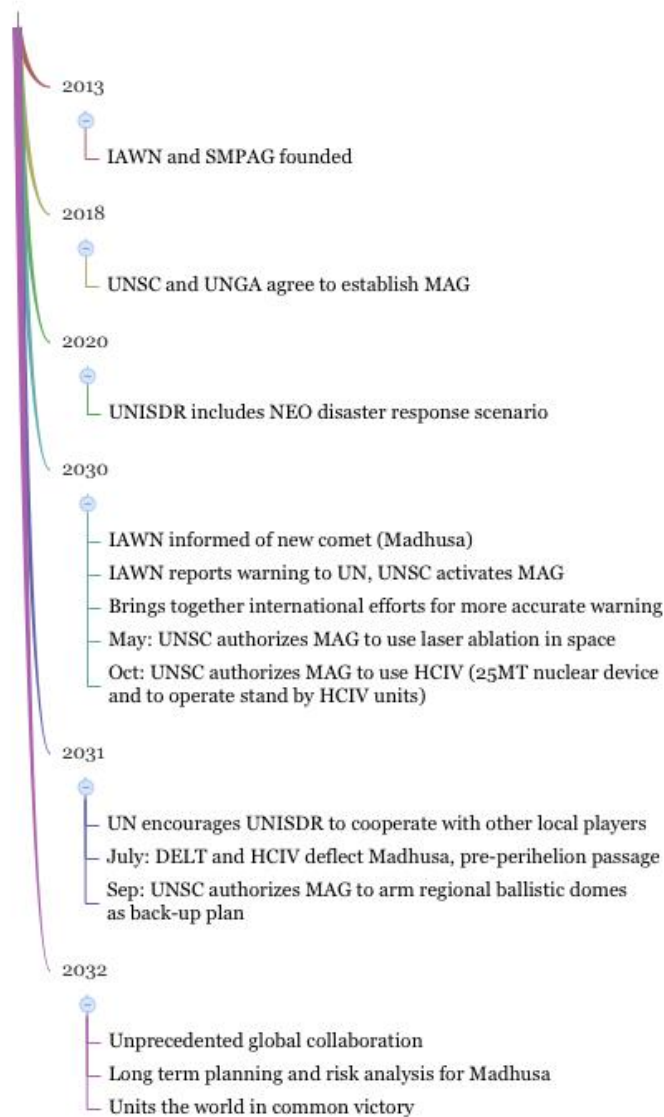
### Optimistic Scenario: Deflection



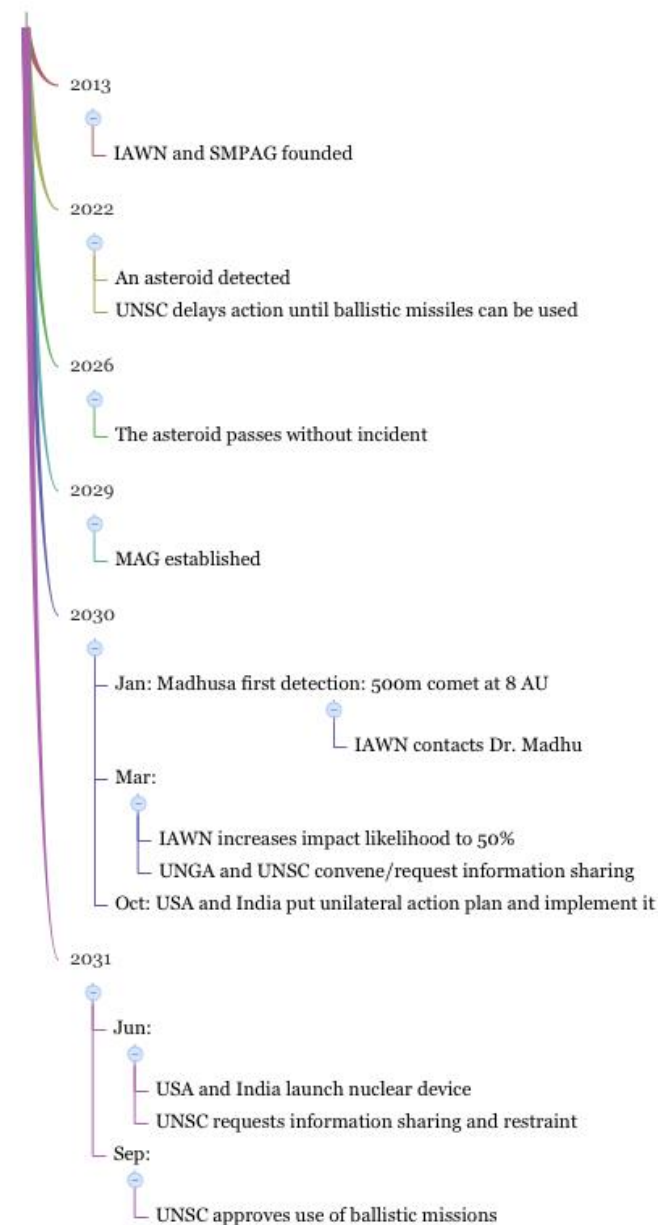
### Pessimistic Scenario: Deflection



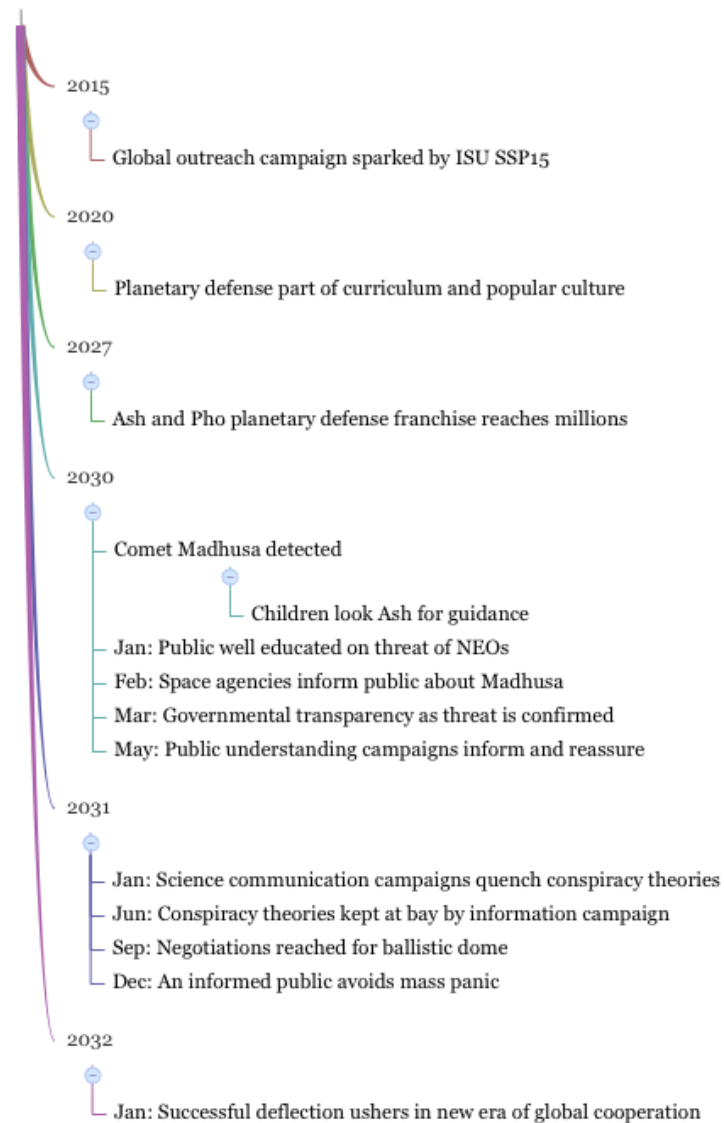
### Optimistic Scenario: Global Collaboration



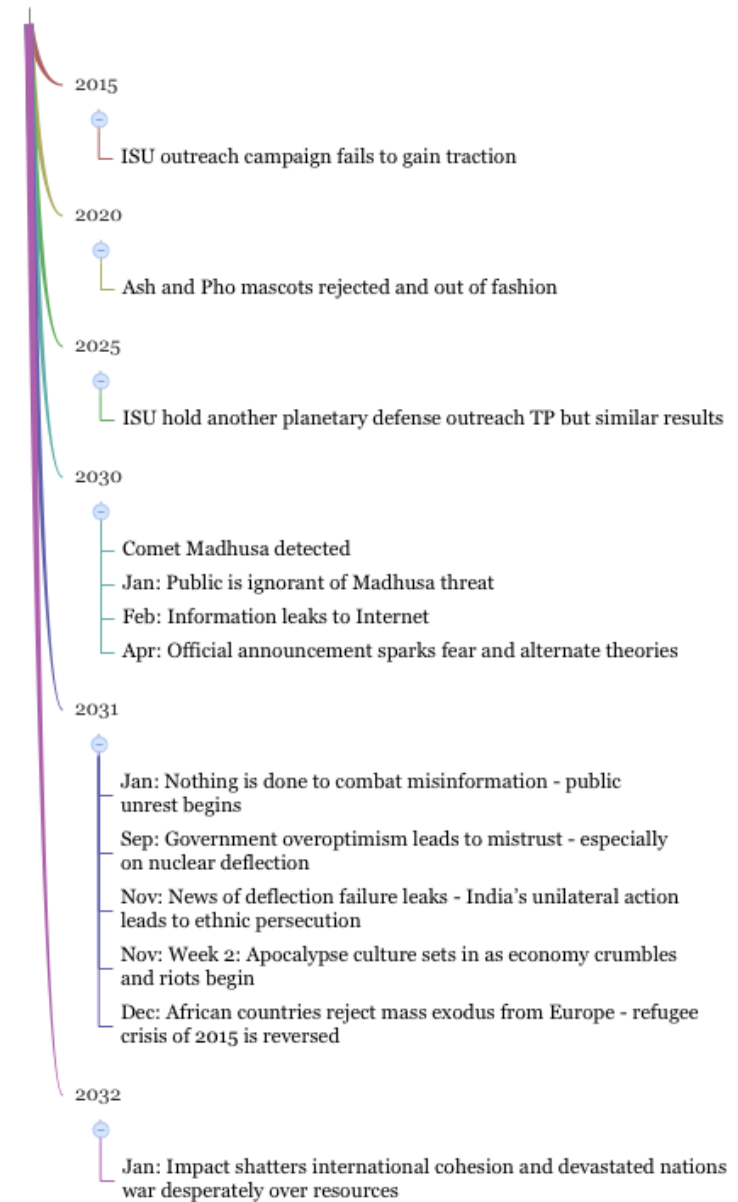
### Pessimistic Scenario: Global Collaboration



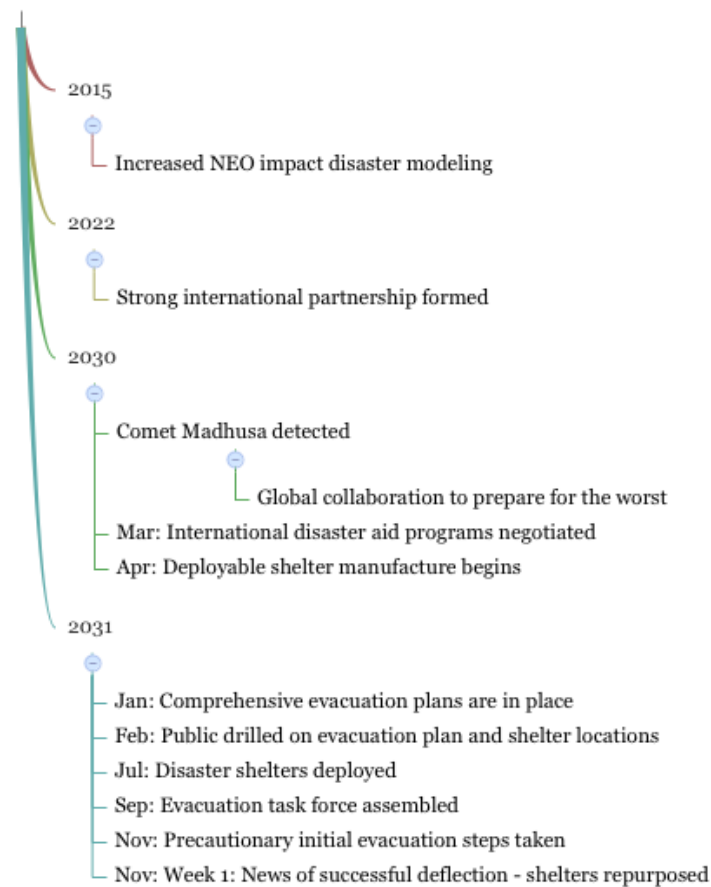
### Optimistic Scenario: Outreach



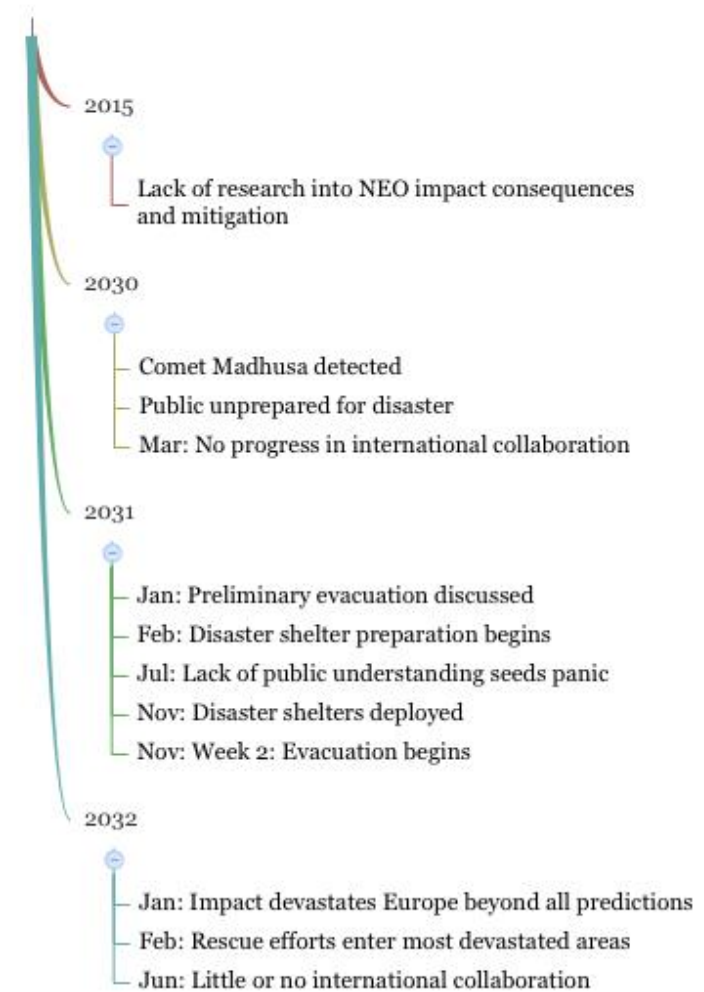
### Pessimistic Scenario: Outreach



### Optimistic Scenario: Evacuation



### Pessimistic Scenario: Evacuation



## Chapter 4. Discussions and Recommendations

### 4.1 Detection and Tracking

Detection and tracking is the most important aspect for protecting life on Earth. Without it, any threat remains unclear or difficult to assess, which results in unforeseen consequences and possibly an inevitable impact of an NEO or a LPC. To overcome this, we recommend the creation of a dedicated Threat Monitoring Network over next decade that fulfills the following requirements:

1. Increasing sky coverage, especially in the southern hemisphere by adding a minimum of two optical observatories in next five to ten years
2. Adding more infrared telescopes at Earth-Sun Lagrange points L1 and L2 by 2025 for better scanning performance
3. Observing regions near the Sun needs be increased to detect NEOs on an incoming trajectory from inside Earth's orbit
4. Building algorithms for data processing and object identification need to be improved to reduce or eliminate human intervention in next 5 years using advancement in computing power
5. Increasing the knowledge of the behavior and composition of cometary nuclei

### 4.2 Deflection

The following list intends to provide a set of recommendations that aims to make the optimistic scenario realistic from the deflection point of view:

1. Reaching an adequate TRL for DES
2. Conducting tests in space by 2025 to validate the thermonuclear option to achieve a sufficient TRL
3. Simulating the ablation effect and further analysis of potential targets must be undertaken prior to designing any nuclear intercept
4. Developing a ground-based ballistic dome solution to enable more flexibility and a redundant deflection architecture

### 4.3 Global Collaboration

Our review of the existing UN activities and groups in the area of Planetary Defense led to the following recommendation. We believe in the creation of a new norm called the Responsibility to Defend Earth, which would be an extrapolation of the R2P. This new norm and its associated actions could be applied upon its implementation in the following five phases:

1. Phase I: Solar System Situational Awareness – a global observation effort
2. Phase II: Technology development – a global move
3. Phase III: Defensive infrastructure deployment – a global concern
4. Phase IV: Being prepared – a global challenge
5. Phase V: Failure – a global disaster

We also believe that the creation of a new global governance body, similar to real global government, to oversee the operation of any weapon technology deployed in space for use in Planetary Defense might be needed in order to proceed effectively, peacefully, and under a deep and strong international trust.



We acknowledge it is possible that none of the above recommendations will be implemented before the discovery of an imminent threat that originates the discussion of a potential unilateral or multilateral response that is not approved by the UN and the implications of such a response.

## 4.4 Outreach and Education

The following list provides a set of recommendations that we believe should be implemented from the outreach and education point of view to reach the level of preparation needed for the optimistic scenario:

1. A younger audience needs to be targeted for outreach and education efforts to inform more people of asteroid and comet threats. Conferences, workshops, and webpages concerning Planetary Defense already exist. The number of people involved however is very limited. By reaching out to children and students, the future leaders and decision makers will be educated, which will give this planet a better chance of survival when it comes to protecting it from potentially hazardous objects.
2. Webpages with visually appealing data as the Asteroid Data Explorer need to be promoted (e.g. Ash). Having an accurate and updated information available to the general public will prevent them from being diverted by false sources or fall for conspiracy theories in case of a real threat.
3. Transparency and a constant information flow in case of a potential strike is essential to avoid panic. Respected and credible speakers need to be put used.
4. The scenario created within KSP needs to be developed further, for example as a mod supported by the KSP community. By involving them in the process, they get educated about the threat and it is a good chance for promoting Planetary Defense further.
5. The mobile game app concept developed within this team project needs to overcome the concept phase. The game intends to educate players by providing real data with which to play. The idea of being the attacker rather than the defender of Earth will attract more people, since it seems to be in human nature to enjoy playing games involving destruction.
6. The mascot Ash together with his counterpart Pho need multiple space agencies to adapt the figure when it comes to Planetary Defense. In such way, people around the world can connect to the same figure. The comic incorporating Ash and Pho shall be incorporated the same way.
7. A badge for scouting organizations should be created to reach out to children and young adults. By earning the badge, kids will learn about the threat and be more prepared to support Planetary Defense. They will learn about the need for cooperation and technology development to help their own community by participating in Planetary Defense projects.

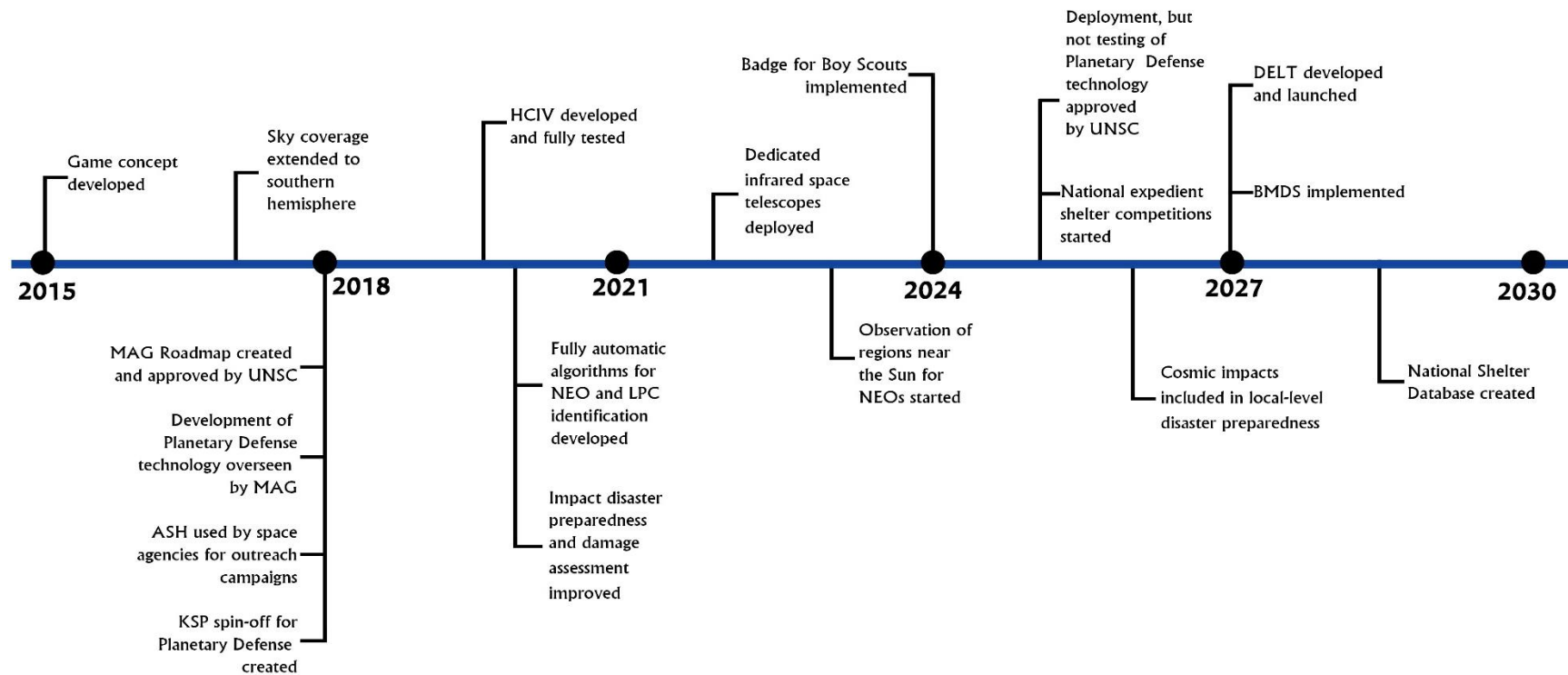
## 4.5 Evacuation and Recovery

Our review of the existing literature related to evacuation and recovery emphasized the importance of disaster preparedness in case of an asteroid or comet impact. The following list provides a set of recommendations that can contribute to a successful evacuation and recovery plan:

1. Each government shall provide to their respective populations accurate information regarding the impact characteristics, its timeline and status of mitigation in order for the population to know in advance how to respond to the threat.
2. Each city needs to include NEOs and LPCs into the conversation about natural disaster.
3. More funding needs to be allocated to research in damage assessment and impact computations to have a realistic idea of impact effects on infrastructure and environment in short and long-term.

4. Remote sensing with specific application in disaster and evacuation management needs to be further developed.
5. Local authorities of the threatened city need to develop an evacuation route and inform all citizens in order to optimize the usage of existing transportation capacity.
6. The energy distribution should be kept on until the final hour of the impact.
7. In case a full evacuation will be needed, governments need to plan in advance when to shut down nuclear power plants.
8. Communications, including the Internet, should be kept online as they can be crucial in terms of alert system and to better coordinate evacuation plan.
9. Each government should create a National Shelter Database specifying all types of shelters that can be used in case of impact and give further information regarding location and accessibility.
10. Coordinating the allocation of people into the proposed hardened shelters should be done by the local authorities responsible for the structures in their area.
11. A website providing detailed design and construction instructions for expedient shelters needs to be developed.
12. A global seed bank and smaller shelters should be developed around the world to provide accommodation for all species of plants and animals endangered by an impact.
13. A global repository of knowledge should be created and kept up to date.
14. A post-impact recovery strategy needs be developed in order to minimize collateral damage and begin reconstruction as soon as possible.

## 4.6 Timeline for Implementation



## Chapter 5. Summary and Conclusions

Comet and asteroid impacts on Earth are a concerning reality and have occurred many times in the past. Small asteroids usually burn up when they enter the atmosphere, but large asteroids and comets could potentially destroy cities. Even worse, an impact by a large comet could end all life on Earth. This is a very unlikely event, but the high impact of it make it necessary to dedicate more efforts to study and research this matter. The READI Project has aimed to tackle these issues during the nine weeks of SSP15.

Detection, deflection, and mitigation strategies are the only way to protect our planet from such threats. Achieving that is a huge challenge, and requires fundamental studies and global preparation well before impact. . The warning time between detection and impact is not always sufficient for successful deflection and mitigation. Major developments for detection are essential especially for detecting large objects that are traveling at very high velocities far from Earth.

We examined and proposed the potential effectiveness of different mitigation strategies for the deflection of comets and asteroids before impact with Earth. We looked at the problem of Planetary Defense from different angles by taking into account the legal, economic, political, and business perspectives, in addition to the engineering and scientific aspects. We need to understand the policy and legal considerations related to a Planetary Defense Program, and analyze the responsibilities of governments and their reaction if an asteroid or comet is on a collision course with Earth. The concern then is not only limited to the technical and scientific aspects, but it expands to the political, legal, and even social and ethical aspects. Therefore, the sooner we start thinking about solutions, the more prepared humanity will be for any impact.

We built a scenario for a given comet threat to give the project a sense of reality, describing two different scenarios: one in which there is insufficient effort and planning, also known as the pessimistic case; and one with a very well planned response, also known as the optimistic case. We decided to take these two extreme situations to generate recommendations that can be applied to other situations. We did this by taking into consideration risks, necessary technology developments, public awareness, and global cooperation efforts. The most feasible solution proposed to deflect Madhusa in our scenario was a combination of three different deflection techniques. We proposed to use DES, TND, and BMD technologies. Time in such a protection program is crucial. Thus, we developed a timeline for the given scenario and responses for detection, deflection, global collaboration, outreach and education, and evacuation and recovery.

The READI Project presents main elements for a complete Planetary Defense Program. We believe that the implementation of such a Planetary Defense Program should be a priority for humanity. As an obligation to future generations, we must act now.

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## Appendices

### Appendix A. Outreach Surveys

Popular culture has poorly informed the general public about the reality of the threats that Earth faces from asteroids and comets and presented erroneous concepts on many occasions. To better understand the level of general public awareness on the issue of cosmic threats and Planetary Defense, we conducted a small survey in several countries. The Outreach Team conducted an information survey to gauge knowledge of the general public's awareness of NEOs. The survey was made available in four different languages to make it accessible to as many people as possible. We have received over 250 responses from across the globe. The participants vary in age and background providing us with a more general understanding. The variation in participants' age and experience is presented in Figure 36 and Figure 37 respectively. The results from the survey suggest that about 60% of the participants are students or professionals working in non-technical fields, and 25% of the student participants have non-technical backgrounds.

The results from the survey presented in Figure 38 show that over 50% of the people who participated in the survey are unclear as to what a NEO is. Lack of public knowledge in this particular area of interest is worth worrying about, even though cosmic impacts rarely occur. If such an impact does occur, it would have massive consequences. Due to the lack of our personal and historical experience of cosmic impacts (Binzel et al., 2013), it becomes even more crucial for society to be more aware of the causes and consequences of such cosmic threats.

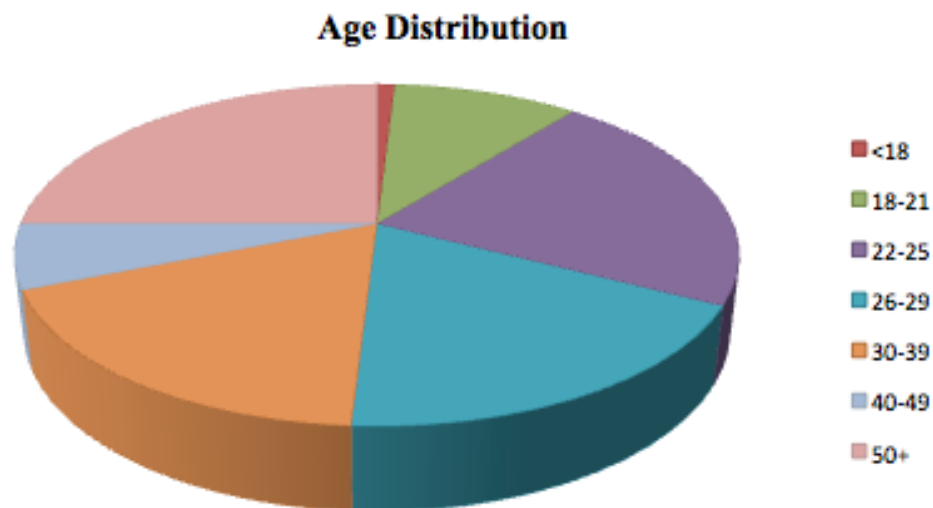


Figure 36: Age distribution of the participants of the survey

### Background Information

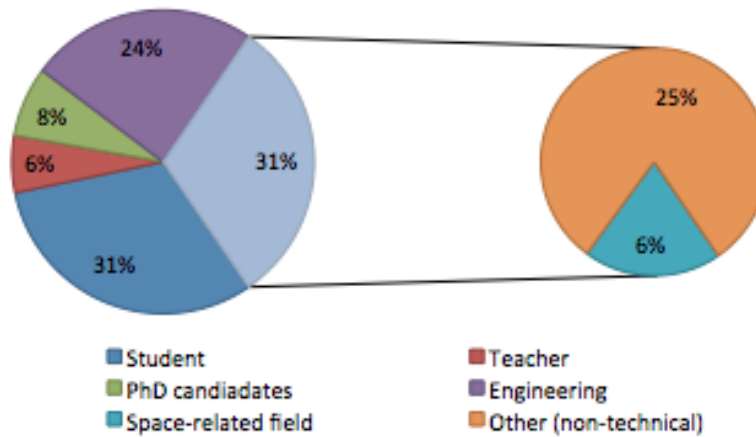


Figure 37: Background of the participants of the survey

### Participants' Knowledge of NEOs



Figure 38: Survey participants' responses to the question "What are NEOs?"

## Appendix B. Application in ISU Departments

This section was derived from the seven ISU Departments in order to look at different aspects of our Planetary Defense project, READI, in an interdisciplinary approach. Ideas and advice from the chairs of these seven departments, as well as from guest speakers were included in this report. The following subsections will discuss each department with regards to Planetary Defense. Even though the discussions are separated into seven subsections, there are some overlaps and connections among them as is the case in any realistic, professional project.

### Space Engineering (ENG)

Space Engineering deals with the mission design for observation, detection, and mitigation technologies of NEOs. This section covers two major challenges in detection and mitigation strategies for a Planetary Defense Program. For detection of asteroids and comets two main technologies currently in use are based on optical and infrared sensors. Optical observations are used by both ground-based and space-based projects. Infrared is mainly used by space-based projects. At present, both optical and IR technologies are quite mature and more emphasis is given to improving the existing technologies of more sensitive and reliable sensors, and bigger optics for the detection of distant asteroids and comets. For early detection, optimum results can be obtained with a combination of ground-based and space-based observations. Ground-based systems are typically optical telescopes. Technologies are matured for these types of telescopes and a current trend is toward building large-aperture, high resolution telescopes that can see deep into the sky. For asteroid and comet detection within our Solar System a 5-6m aperture telescope is sufficient to detect most of the objects within a 10 AU distance from Earth. All ground-based telescopes are limited by the requirement for a clear sky and their observational capability is limited to around 20-22 days in a month. Having multiple telescopes located in various geographical locations will be useful for increasing the detection probability. Typical realization time for these types of telescopes is 4-5 years.

Space-based telescopes are best suited for continuous scanning of deep space as they do not have any of the weather limitations. For detection of many objects with very low albedo, infrared telescopes are preferred. The preferred location for these telescopes is the Earth-Sun L2 point because of the reduced thermal constraints (Farquhar et al., 2004). Earth-centered orbits as well as other Lagrange points like L1, L4, or L5, can also be considered. In fact having multiple missions covering both Low Earth Orbit (LEO) and the libration regions will give us better coverage of the sky. Typical time frames for realizing these projects vary from 4-7 years.

There are many engineering challenges for mitigation techniques. Asteroid and comet mitigation techniques exist with moderate Technology Readiness Levels (TRLs) such as:

- Nuclear explosion
- Nuclear-based high-thrust, high-specific impulse propulsion systems
- Gravity Tractor – useful when we have an early detection of around 10 years or longer

Currently none of these technologies have been demonstrated and field proven. Also, once we have some definitive orbit for a PHO, this kind of mission may take 7-8 years to realize. So it is highly recommended that we do the preparatory work well in advance. That would include identifying a probable launch vehicle for the proposed mission, and being ready to launch on as short notice as a few months. Other techniques that will become realizable through technological advancement in the near future including laser ablation systems. However, to achieve a high TRL and threat mitigation level, we need to test these technologies.

This kind of test mission may call for multiagency and multinational cooperation in terms of technology and resources.

### **Space Sciences (SCI)**

The detection of NEOs is essential for preventing a future impact. Some programs are already in place at different space agencies and observatories, but there is still a lot to do to improve the detection of more and smaller objects to allow time to react in the case of an impending impact. Detection is important, but the characterization of NEOs and LPCs is also crucial to be able to deflect them successfully and to simulate the Earth impact effects. The most important characteristics to learn are the size, density, velocity, and angle of entry in the atmosphere as well as the NEO composition (Collins et al. 2005).

After the 2013 asteroid airburst in Russia, some observatories revised their programs to incorporate more time for detection of NEOs. The NEOWISE satellite was repurposed in 2013 by NASA to monitor space in the infrared to detect NEOs. It has found a few thousand objects larger than 100m (Mainzer, 2012) while the Sloan Digital Sky Survey (SDSS), and the Large Synoptic Survey Telescope (LSST) are also used to find asteroids.

A way to improve detection is to develop more powerful instruments on existing ground-based telescopes - especially for detection of low-brightness objects - and detectors that could cover a large part of the sky with a wide field of view. Also, to improve detection, it is important to cover the entire sky in both the northern and southern hemispheres, and to have a program to divide the sky into several portions that are monitored by different observatories. Increasing the frequency of this kind of survey allow more time to help in the discovery of more NEOs and LPCs.

For detection, one idea is to have more space-based telescopes in infrared, and more ground-based telescopes in the visible spectrum. Also, a new method has been proposed recently using LIDAR, active remote sensing, to illuminate NEOs to detect them. This project is called DE-STAR (Riley et al. 2014) and the goal is to detect smaller NEOs with diameters under 100m.

Another important issue to consider is the development of new telescopes that will be in operation in the next decades. We will have a completely new generation of telescopes, e.g. the Thirty Meter Telescope (TMT) and the Extremely Large Telescope (ELT) of 30 and 42m respectively. Also in the next few years, several larger radio telescopes will be in place.

Another problem with detection is to observe in the direction of the Sun. If a comet or asteroid comes from the direction of the Sun relative to Earth, it is really difficult to observe and consequently there is not much time to react. Solar telescopes such as the Large Angle and Spectrometric Coronagraph Experiment (Solar and Heliospheric Observatory) are able to observe the Sun and also the objects around it. This would be a way to identify comets passing just next to the Sun, but this would only provide a limited time for preparation on Earth. Even with these instruments in place, good detection in the direction of the Sun remains very difficult. Infrared and visible observations are needed for characterizing an asteroid to determine its size. Spectroscopy is the best way to obtain all information about the composition, velocity, and density of an object.

### **Space Applications (APP)**

The need to have a minimum TRL to counter the threat of Earth bound asteroids and comets is now being addressed at the international level after the Chelyabinsk meteor air burst event in 2013 in Russia. The term Planetary Defense includes everything from solar weather to space debris to NEOs. A current problem faced today with asteroids and comets is proper characterization and early detection. To overcome the characterization problem effectively the idea is to send probes or landers on their surfaces. The recent Rosetta mission has demonstrated this technology. Elevation models and 3D surface mapping using LIDAR and radar imaging of the core can be generated. For detection purposes optical sensor have to be used extensively. The accuracy of a conventional radar system can be increased by using a spatially separated antenna. This setup is called radar interferometry and it augments the optical detection rate (Van Westen, 2000).

Detection of asteroids and comets is highly dependent on the object characteristics. If an asteroid has low reflectivity it becomes highly difficult to detect with existing telescopes. If a comet is coming from far out in the Solar System, it becomes difficult to properly characterize, because of its high inclination orbit and velocity. The only solutions are to use infrared remote sensing and to have a constellation of satellites positioned at specific altitudes and points just for surveying and detection using infrared, optical, and photometric systems (Borucki and Summers, 1984).

### **Space Policy, Economics, and Law (PEL)**

PEL is mainly focused on international policy and legal aspects to make all discussed technical solutions possible through international consensus. Considering the current international legal regime, to use nuclear devices in outer space requires new international agreements. To mitigate impact consequences should be part of an international cooperation also. Cost wise, global collaboration is more desperate. Any single nation cannot bear the cost to detect and deflect asteroids and comets. International cooperation can be done at various levels, from bilateral to global collaboration. Suppose the threat is a small size asteroid that would only affect a few countries. In this case multilateral cooperation would be more likely. Or if it is detected with only several months' notice, international cooperation would be hard sought because of the necessity for an urgent response. Nevertheless, global collaboration should be considered as a primary approach because theoretically any country could be hit. PEL will be dedicated to make global collaboration more than bilateral or multilateral cooperation. Existing international organizations such as the UN will be worthy starting points to look into global collaboration. Recently several nations and space agencies initiated plans for asteroids and comets, while UN COPUOS has started working to make these efforts more cohesive. For instance, IAWN has been established under UN COPUOS and is making a global network for detecting asteroids and comets. Yet a proper decision making process and groups for execution do not exist in the UN. A possible International Mitigation Action Group (MAG) within the UN will be one of two focal points of PEL (Davis, 2015).

The role of the possible MAG would be determined primarily by current political dynamics and the legal regime of the UN. The Global Collaboration subgroup is bearing two rudimentary ideas. One is that the Security Council delegates' authority to MAG to execute Planetary Defense operations. Another is incorporating MAG into the Security Council as a part of it. Both ideas have merits and demerits but both aim at facilitating rapid and feasible decision making. Planetary Defense execution is seen to be hardly acceptable based on the current legal regime of the UN, such as OST which does not allow any deployment of weapons in outer space, in particular nuclear weapons. In the worst case deploying or using nuclear

devices for deflection must be accepted by all human beings. This should be considered from multiple perspectives, such as a country who is under threat from an asteroid or comet strike whereby a Planetary Defense initiative can be taken by another nation who has the technological capability to help. “First, it is doubtful whether such a responsibility constitutes a rule of international law. Second, it is unclear whether it establishes an obligation to take action. Third, it raises the question of violation for sovereignty of the state in which the intervention takes place” (Tronchetti, 2015). PEL puts into perspective these issues and helps identify a proper legal base.

### **Space Management and Business (MGB)**

In recent years, the political will to tackle Planetary Defense has grown, but the funding required to develop and deploy new technologies and global defense plans has been slow to materialize. As mentioned earlier, our team is working with a two year timeframe from detection to impact, giving humanity just two years to launch and rendezvous orbit-deflecting technology. The intervention strategy therefore depends not only on the size and type of incident object, but on the time elapsed prior to detection during which technology can be developed and put into readiness. From an economic point of view, robust action is possible only with the commitment of at least hundreds of millions of dollars from international governments. In the meantime, some of the most vocal groups are private initiatives- asteroid awareness campaigners not part of the government that take matters into their own hands. Finally, the case for a business opportunity might be made around incentives to support sky surveys and Planetary Defense.

### Government

A clear and inevitable external threat can spark a Planetary Defense Program on a scale not seen since the Apollo program. However, without a defined threat, governments may fall into the trap of disregarding low probability events, even if the risks could be catastrophic. This leads to a shortfall in funding for NEO detection and deflection research. Some space policy experts even say the best thing to galvanize a global Planetary Defense initiative would be for a medium sized asteroid to hit relatively soon. The 17m asteroid that exploded above Chelyabinsk in February 2013 did cause some politicians to call for countermeasures, but still without any significant accompanying surge in funding.

In 2010 the U.S. National Research Council (NRC) report (National Research Council et al., 2010) concluded that an increase in one order of magnitude of annual funding from \$5 million to around \$50 million would be sufficient to support a comprehensive observation program and achieve the goals set out by the George E. Brown Jr. Near-Earth Object Survey Act of 2005 stipulating that 90% of asteroids between 140m and 1km in diameter be found by 2020. A further order of magnitude in funding to \$250-500 million was deemed sufficient to allow the US to truly take asteroid detection into its own hands, completing the survey goals with redundancy and supporting development and space testing of deflection technology.

Lead asteroid deflection researcher, Bong Wie of Iowa State University, was granted US \$600,000 from 2011 to 2014 from NASA’s Phase I and II grants to develop a robotic Hypervelocity Asteroid Intercept Vehicle (HAIV), which would deliver a kinetic/nuclear payload (Wie, 2013). However, around \$500 million to \$1.5 billion would be needed to build and deploy a HAIV test mission to target an asteroid (Pitz et al., 2012a).

We cannot be complacent in nuclear intervention as having nuclear weapons in space is a highly sensitive issue. Consequently, it is crucial that we find the money to support significant advances in politically tractable asteroid deflection methods.



### Private/Non-profit

B612, a private non-profit foundation, was set up to raise US \$450 million to fund an infrared asteroid hunting space telescope called Sentinel. Their goal is to make a significant contribution to the discovery of 90% of the near-Earth asteroids with diameters larger than 140m and a large number above 30 m. However fundraising has only managed to raise US \$1.2 to 1.6 million between 2012 and 2013, far short of their US \$30 to 40 million annual goal (Watson, 2015).

The Emergency Asteroid Defense Project (EADP) is a Copenhagen-based global non-profit initiative to develop small HAIV-style spacecraft that can deflect or disperse asteroids and comets with only a few days warning, by means of a nuclear device. They tried to raise \$200,000 through a crowdfunding campaign but only achieved 4% of this in two months. It seems that crowdfunding is not very useful at this time due to lack of public awareness.

### Future business opportunities

Insurance: Once an asteroid impact becomes more imminent the predicted increase in public awareness would inevitably give rise to a completely new insurance market. Both private and public organizations are likely to spend significant fortunes to insure themselves against the possible damage. This new source of funds could then be allocated to impact mitigation endeavors.

Space escape: An imminent asteroid impact is expected to materialize some of the well-known science fiction scenarios in which decision makers, billionaires, and others can guarantee their own well-being by means of super expensive lifesaving solutions such as an ad-hoc space habitats. If invested wisely these sources of funds could potentially be used to benefit all of humanity by developing a global ground-based evacuation, rescue, and recovery infrastructure that would eventually allow substantial growth in revenues.

Asteroid mining: The costs involved an asteroid mining venture have been estimated to be around US \$100 billion (Lee, 2012). To justify financial feasibility the return on investment should be around 30% at least. An asteroid mining company such as Planetary Resources might see an approaching asteroid as an opportunity to acquire unlimited funds to improve their technology, simultaneously gaining global respect and reaping the mineral riches of the asteroid.

### **Human Performance in Space (HPS)**

If a threatening asteroid or comet is detected, humanity needs to work together as a group, and it would be of prime importance to note how society responds to such situations. Regarding countries and larger groups, it is vital that countries band together and that this is not based on ethnic or geographic lines. From the HPS perspective you have to hope for the best, but plan for the worst. If societal structures start breaking down, how do you protect people? How do you ensure that things continue to function in a way that is beneficial for all people? To answer this you need to look into psychological tools to make sure people cooperate and do not panic. People in charge of asteroid disaster management may need to use propaganda to make people behave as needed. Even if this may not benefit the individual directly, it will be beneficial for society as a whole (Lehnhardt, 2015).

From a psychological perspective if you are the person in charge of controlling a group of people while they are preparing for a potential or inevitable impact, finding ways of making people do what you want them to do is very difficult. Manipulating people to do things is a sensitive issue in society but could be essential for the survival of the human race in the event of an asteroid or comet impact. People need to

perform and behave in a certain manner in the event of the detection of an asteroid or comet that is on a collision course with Earth, and this is a subject of psychological study (Lehnhardt, 2015).

In the event of a mass extinction impact, the human race would need to find a means for preserving enough of the Earth's life to enable basic ecosystem services for any future planetary habitation. Such an attempt at preservation would not necessarily require the traditional "Noah's Ark"- style removal of large quantities of flora and fauna; rather, the DNA of a large number of plant, animal, and microbial species could be preserved in their embryonic states or potentially digitally for replication in the future. While not all of these technologies are mature enough yet to accomplish these procedures, it is critical to take as many sequenced genomes as possible. In taking genetic material, both from humans and other life forms, genetic diversity is absolutely critical (Lehnhardt, 2015). Genetic diversity is an essential component for generating human colonies on other planets. Each pairing of people would need to create more diversity, if too much breeding occurs within a small group, genetic diversity reduction would result in more genetic malformations. Thus, there would likely need to be a strict selection process for sending people away from Earth. People would not be able to select their mates, they would have to be chosen for them based on genetic variability, and so just choosing people who were married may not work; people would need to be genetically compatible. A similar selection of genetic diversity must occur among the other life forms preserved to ensure the best possible defense against genetic malformations and disease. Under the current environment, where no existential threat exists, there is likely no ethical viability for such a selection process that restricts individuals and mandates breeding partners (Lehnhardt, 2015)

### **Space Humanities (HUM)**

In the event of an incoming NEO, it is important that people be aware of the nature of the threat as well as the consequences of an impact. A communication plan targeting a large audience should also be used as a means to convince people of the necessity of Planetary Defense mechanisms, to set off a political debate on the subject.

First, from the Humanities standpoint, our team decided to focus on education and entertainment, as well as communication toward decision makers. To tackle the point while considering today's world, we decided to use modern media and rely on networks already in place with an existing audience and similar approach to get our message out. In recent years, different organizations from around the globe, ranging from the Secure World Foundation to the Asteroid Day Foundation more recently, have been trying to find ways to bring the issue outside of the space community. In this respect, the overall goal of our outreach campaign will be to provide visually appealing material that is easy to read and to share on social media (Patten, Dahlstrom and Steeves, 2015). Decision makers can be impacted by any outreach campaign reaching a critical mass of the population. On top of that, organizations such as IAWN, SMPAG, and IDPAG, created after the work of the UN COPUOS STSC Action Team 14 (Office of Outer Space Affairs, 2013), will provide leadership with information on the threat and on the possible mission plans. From the outreach point of view, giving politicians a way to visualize the scientific data in an easily readable fashion is an effective way to bridge the gap between the public and the community of scientists and engineers.

Second, it is important to realize that Planetary Defense is a long term and global concern, yielding two key objectives. First, targeting children and students is of paramount importance, because the new generation will need to pursue the efforts and possibly face the next major NEO threat. Also, a global issue should imply a global communication plan. It is necessary to ensure that people are equally given the means to become educated about the problem, both at the public and governmental levels. Furthermore, as suggested

in the results of a recent exercise, “there could be much distrust and misunderstanding when an actual threat is discovered” (PDC, 2015). Another report has studied this issue, describing a possible communication strategy to deal with a NEO threat and emphasizing the necessity to “reassure the public” and “secure that the spread of false information is minimized” (Emanuelli et al., 2014). The medium-term strategy presented involves scientists’ appearances in media and accurate communication, without either under or overstating the threat, since either could result in unwanted public reactions. The spread of consistent information across the media is a way to ensure that confusion will not appear in the public’s opinion because of conflicting points of view given by experts or journalists using different data sources. In the long term, developing a complete educational program is recommended to “provide the population with the competency to understand and discuss the threat” (Emanuelli et al., 2014). People with at least a basic understanding of the problem are less likely to be affected by the minority discrediting the scientific facts. Therefore, it will reduce opposition by the public towards action taken by governments and also make it easier to act quickly in case of an emergency.

Our analysis also considers the spiritual aspects of the endeavor, and takes into consideration that different religions have very different views on space exploration in general. Scholars have always actively debated the importance of religion in human scientific and technological progress. Planetary Defense initiatives could greatly benefit from the support of representatives from various religious groups. Indeed, as a study by the IAA suggested in 2009, “it will be important to recognize the role of religion, superstition, and myth to effectively communicate risk” (Bekey, 2009). This reflects an important aspect of the long term stakes of public awareness about the NEO threat: a significant part of the endangered population will refuse to listen to the scientific explanations if they are not endorsed by religious institutions. Moreover, different cultures and spiritualities would result in different behaviors in the event of an impact or threat of impact. With the risk being theoretically the same in every place on the globe, emergency plans and communication will need to take this variety into consideration. The same study cites Professor David K. Chester, from the University of Liverpool, who explained that “religion is an essential element of culture and must be carefully considered in the planning process, and not simply dismissed as a symptom of ignorance, superstition, and backwardness” (Chester, 2005). The international community, while developing emergency procedures and during the aftermath of an impact, will have to understand the culture of the people and work closely with the local religious communities. The large number of possible casualties, should a NEO strike a densely populated area, will require help from every layer of society to keep chaos from spreading and to recover quickly after the impact.

From an ethical point of view, such an impact in a metropolitan area could lead to unprecedented numbers of injured people who would require medical care. The lack of available infrastructure and limited resources in the aftermath can be compared to previously encountered disasters, such as Hurricane Katrina, which hit and resulted in flooding in New Orleans in 2005. This raised huge ethical issues about human medical care. In a publication about the events at the Memorial Medical Center in New Orleans, Dr. Pou, who was supervising operations there during Katrina, explained that “the conditions faced were similar to battlefield operations” but that “there’s nothing that teaches [...] military evacuation strategies” (Okie, 2008). Indeed, the evacuation forced the medical team to turn to reverse triage, dealing with the healthiest first, because they considered it to be the most efficient (Parent, 2015). There were no defined guidelines whatsoever and decisions made by politicians when facing the emergency situation did not protect teams “from lawsuits or criminal prosecution” afterwards. Moreover, medical teams were not prepared to face a helpless situation where they could not rescue people, only by lack of resources. Recommendations issued after Katrina, such

as developing “public debate about [...] decision making when resources are limited” could be used in the development of NEO threat emergency procedures. Indeed, such a critical situation may require personnel to make decisions opposed to what could be standard at any other time. Those new standards need to be clearly defined by the authorities, explained to the public, and taught to the medical personnel, preferably using simulations and considering the psychological and ethical aspects.

## Appendix C. Current NEO and LPC Detection Projects

### Current ground-based technologies

After the approval of the Authorization Act in 2005 (U.S. Government Printing Office, 2005), NASA provides support to many discovery teams, follow-up observations, and physical characterization observations. In particular, the primary discovery programs in the US are:

- Catalina Sky Survey: a project based at the University of Arizona that operates two telescopes in the Tucson area providing comprehensive sky coverage, employed also for follow-up observations (Yeomans, 2015).
- Pan-STARRS (Panoramic Survey Telescope and Rapid Response System): run by University of Hawaii at Haleakala Observatory, Hawaii, since 2014. It is devoted only to search for NEOs and some follow-up observations that look at the faintest objects not currently detectable by other systems (Yeomans, 2015).
- LINEAR (Lincoln Near-Earth Asteroid Research): an MIT Lincoln Laboratory program operated in Socorro, New Mexico, that is complemented by the 3.5m Space Surveillance Telescope currently operational on Atom Peak, New Mexico funded both by NASA and Defense Advanced Research and Projects Agency (Viggh, 2015; Yeomans, 2015).
- Spacewatch: based in Arizona, the first group to employ a sophisticated telescope devoted exclusively to the search of NEOs. It recently transitioned from an emphasis on the discovery of NEOs to follow-up observations (Yeomans, 2015).

From the European side, the NEO segment of the Space Situational Awareness program (Bobrinsky and Monte, 2010) is currently ESA's major asset in this field. Although there are telescopes in Europe such as the ESA Optical Ground Station in Tenerife (Spain) (Koschny, Busch and Drolshagen, 2013), La Sagra Sky Survey, (La Sagra Sky Survey, 2012) and the Campo Imperator Near-Earth Objects Survey, (Boattini et al., 2007) that made some significant discoveries in the past, ESA cannot compete with NASA's supremacy. These telescopes are used mainly for tracking already discovered objects. In 2014 ESA made an agreement with European Southern Observatory to use the 8.2m Very Large Telescope in Cerro Paranal (Chile) to perform more precise searches and tracking of NEOs. (ESO, 2014a)

The Russian Federation is also contributing to NEO follow-up observation through its International Scientific Optical Network (ISON) of small telescopes spread throughout the world. In addition, the Moscow State University operates the Mobile Astronomical System of Telescope Robots, a network of ground based telescopes located in the Russian territory (Shustov, 2014).

Japan is also contributing through its Japan Spaceguard Association, performing other follow-up and physical observations of NEOs mainly through its Bisei Spaceguard Center. (Okumura et al., 2012)

Additional spectroscopic observations are made in the infrared band by the NASA Infrared Telescope Facility atop Mauna Kea in Hawaii. (Tokunaga and Jedicke, 2006)

Radar telescopes can be used for precise orbit determination and characterization of NEOs. Before characterizing a NEO it is essential to point the narrow radar beam towards the known location of the object, and the target must be sufficiently close to Earth to be characterized properly. Despite these difficulties, radar is one of the most effective methods to track NEOs, therefore gives the best hazard assessment. (NAP, 2009).



Currently, the two most capable telescopes that perform radar observations fundamental to characterizing the identified objects in terms of shape, size, spin rate, composition, and orbit are:

- The Goldstone Observatory (California) shown in Figure 39(a). It is a 70m antenna that can cover 79% of the sky from  $-35^{\circ}$  to  $+90^{\circ}$  in declination (NASA Antennas, 2015; NAP, 2009).
- The Arecibo Observatory (Puerto Rico) shown in Figure 39(b). It is the world's largest single-dish telescope (305m diameter) placed in a large limestone sinkhole (NAIC, 2015). It is 20 times more sensitive than Goldstone radar telescope and can see declinations from  $-1^{\circ}$  to  $+38^{\circ}$  with a sky coverage of 32% (NAP, 2009).

Additional radar observations are performed by the Evpatoria 70m radio telescope in Crimea (Konovalenko, Lytvynenko and Klooster, 2003), and China is building the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in a karst depression in the Guizhou province of southwest China. It will be the biggest radio telescope in the world when it begins operations in 2016 (Nan et al., 2011).

Another fundamental role is played by the amateur astronomer who follows up on the newly discovered objects posted in the MPC NEO Confirmation Page (IAU, 2015) to increase the precision of the orbit determination (Yeomans, 2015).



Figure 39: Radar telescopes: (a) Goldstone 70-m antenna, (b) Arecibo Observatory (Source: Wikipedia)

### In Development Ground-Based Telescopes

The Asteroid Terrestrial-impact Last Alert System of the University of Hawaii will complement the Pan-STARRS survey by the end of 2015. Up to 8 telescopes will look at the available sky twice a night. It is expected that this system will provide an alert on the order of days to weeks for NEOs tens of meters in diameter on impact trajectories with the Earth. (Tonry and Good, 2015)

The Large Synoptic Survey Telescope is currently under construction in northern Chile, and will start full operations in the early 2020s. It is a Public-Private partnership and will be an important resource for optical observations in the southern hemisphere. (LSST, n.d.)

In addition to this, the Catalina Sky Survey and the Las Cumbres Observatory Global Telescope Network (LCOGT) are partnering for building a network of three 1-m telescopes on Cerro Tololo (Chile). This will contribute in overcoming the lack of professional ground telescopes in the southern hemisphere, after the



Siding Spring Survey in Australia was closed in 2013. The specific focus of Catalina LCOGT Asteroid Southern Survey will be for NEO discoveries. (Christensen, 2014a; Christensen, 2014b)

ESA has carried out extensive simulations for the proposed Wide Survey program. Its innovative “fly-eye” telescopes will be located in at least three sites around the world, and will aim to discover very small NEOs (10-50m in size). Moreover, the telescopes are expected to cover the visible sky daily. (Di Pippo and Perozzi, 2015)

### **The NEO observers from space**

Currently, there is only one functioning infrared space-based telescope in polar orbit around the Earth to detect NEOs. The WISE spacecraft shown in Figure 40 was reactivated in 2013 after 2.5 years of hibernation, now called NEOWISE, for an additional planned period of 3 years. The previous focus was to survey the entire sky in the infrared waveband, while its current exclusive goal is to discover and characterize NEOs. This space telescope needs follow-up observations from the ground to confirm its discoveries (The NEOWISE Project, n.d.; Yeomans, 2015; Mainzer et al., 2015a).

Canada launched its own space telescope in February 2013. NEOSat, a microsatellite dedicated to performing both SSA (satellites and space debris) and asteroids detection (Canadian Space Agency, 2015). By March 2014 it had not acquired any scientifically useful data due to technical issues (Wallace, Scott and Sale, 2014).



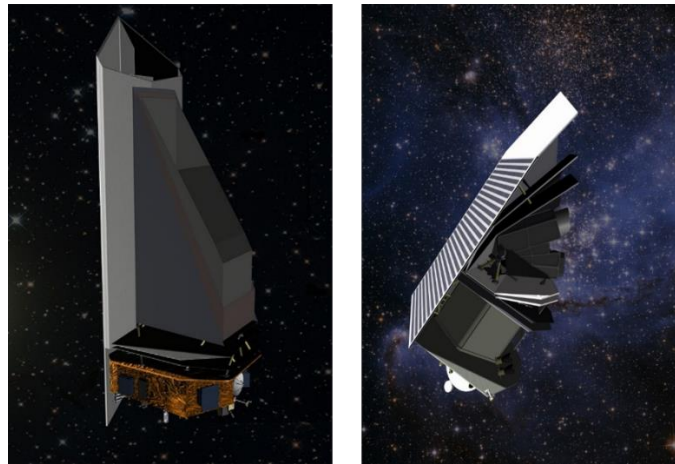
*Figure 40: Artist's concept of the WISE spacecraft (Source: Wikipedia)*

### **Proposed and in-development space observatories**

NASA is currently developing its new NEOCam space observatory, shown in Figure 41(a), which will operate in near infrared wavelengths to discover and characterize potentially hazardous NEOs larger than 140m in diameter. (Mainzer et al., 2015b).

In addition, the nonprofit B612 Foundation is proposing its Sentinel space observatory, an infrared space telescope that is planned to be launched in 2018, shown in Figure 41(b). It will orbit close to the Sun on an inner orbit with respect to the Earth, in order to detect and characterize NEOs that can be potential threats for Earth. Thanks to its high accuracy it will be able to detect objects that could strike Earth up to 100 years in advance (Reitsema and Lu, 2015).

Russia is planning to implement Ekozont, a new space system consisting of one or two space telescopes for hazardous celestial objects and space debris detection, scanning the entire sky in one day. It is expected to be launched by 2021 (Shustov, 2014; Shugarov et al., 2015).



*Figure 41: Artist's concepts of the (a) NEOCam and (b) Sentinel space telescopes (Source: Wikipedia)*

## Appendix D. List of Most Relevant Websites About Planetary Defense

### Websites related to official agencies

- ESA Space Situational Awareness: <http://neo.ssa.esa.int/web/guest>
- NEO Program NASA JPL: <http://neo.jpl.nasa.gov/>
- Minor Planet Center: <http://www.minorplanetcenter.net/>
- NEOCam: <http://neocam.ipac.caltech.edu/>
- NEOWISE: <http://neowise.ipac.caltech.edu/>
- UNOOSA: <http://www.unoosa.org/oosa/en/ourwork/topics/neos/index.html>

### Non-profit Projects

- Sentinel Mission (B612 Foundation): <http://sentinelmission.org/>
- Emergency Asteroid Defence Project (EADP): <http://eadproject.com/>, <http://asteroiddefence.com/>

### Other Websites / Sources

- The Spaceguard Central Node: <http://spaceguard.rm.iasf.cnr.it/>
- Spaceguard UK: <http://spaceguardcentre.com/about-us/>
- Secure World Foundation. <http://swfound.org/resource-library/planetary-defense/>
- Planetary Defense Conference: <http://www.pdc2015.org/>
- National Space Society:  
<http://www.nss.org/resources/library/planetarydefense/planetarydefense.html>

## Appendix E. Outreach Game Mechanics

**Player** - The player shoots the asteroid or comet from a canon, sending the object into an orbital trajectory on a collision course with Earth. The user simply selects from a list of asteroids and comets that are available to use on a given level.

**Orbital Trajectory** - Depending on the speed and accuracy with which the player slings the asteroid or comet, the object will strike a location on Earth. The user will have suggested areas to impact in order to gain the highest possible score. Upon hitting the suggested areas, the defensive capabilities on Earth will quickly increase with improved technologies deflecting or destroying the user's future asteroids and comets. Therefore, the player will have to choose the most effective form of NEO to use in order to break down Earth's barriers.

**Improved Difficulty** - To break down these improving defenses as the game progresses, the player can strike specified research centers/stations that are building Earth's defense systems. These areas would be highlighted on the map. A preview of a directional path for the comet or asteroid to strike important locations will be shown briefly. Then the player would choose where they want to fire the object. Striking strategic targets slows down the development of defense systems on the planet, enabling the player to impose greater destruction and thus a higher score.

**Asteroids and Comets** – The player will begin with a small selection of asteroids and as they progress throughout the game they will gain access to a variety of larger, faster, and varied composition asteroids and comets. Each type of asteroids and comets will have different destructive capabilities. However being more destructive is not necessarily the best choice. That will depend on the goals of each level. Additionally, each object will respond differently to the defense mechanisms of Earth. For example, the metallic asteroids will cause the largest damage but may be more susceptible to defense mechanisms while certain types of comets will create cluster shots that cause impacts over a wider area. A tutorial will outline the pros and cons of each type of asteroid and comet as they become available in the game. In doing so the participant is learning about the hazards of NEOs and LPCs and can apply their new knowledge when playing the game.

**Destruction and Points System** - The player will earn points for causing various type of destruction based on the level they are on. For example a player may need to cause a tsunami to take out multiple locations or use an airburst to level a city. Points are tracked in number of casualties and cost of damage caused. Before selecting an asteroid or comet, the player can select the information box that outlines the effectiveness of each object. Each type has varying degrees of damage infliction. A table shows the damage the asteroid can inflict, e.g. which one is best for generating the largest tsunami, destroying cities, or to potentially break up into multiple pieces when entering the atmosphere etc. As the player selects their desired type of NEO or LPC, the information box appears on the screen describing the object. This will not be too technical but will give general information about the object. Additional information can be sought by selecting the links from the main screen that take the player to an educational asteroid/comet awareness website. If the user is part of Facebook, Twitter, or any other social media they can share this information to spread the word about PHOs.

## Appendix F. Existing Evacuation Techniques

### Local Level Strategy

FEMA (Federal Emergency Management Agency) is the main governmental body in the United States that deals with evacuation strategies and all elements related to that. The main elements that should be taken in consideration by the global community are outlined below.

Massive evacuation key considerations:

- Lead time required to conduct mass evacuations.
- Limits in weather forecasting.
- Interdependencies between shelters and transportation.
- Special needs of children.
- Special needs populations.
- Animal evacuation.
- Critical infrastructure.

Concept of operations:

The conduct of evacuation operations is generally a state, tribal, or local responsibility. However, there are circumstances that exceed the capabilities of these jurisdictions to support mass evacuations. The operational concept of the evacuation should include the following considerations:

- Functions and responsibilities
- Coordination and communications
- Transportation, fuel, etc.
- Mass care, emergency assistance, housing, and human services
- Public health and medical support
- Public safety and security

Responsibilities:

The specific roles of governments in evacuations vary from state to state. In general, state laws in the US provide the Governor with authority to declare an emergency and assume extra powers and responsibilities to protect the health and safety of the citizens of the state. Specific powers relating to an evacuation include:

- Creation, amendment, or rescinding of rules or directives to provide the necessities of life or supplies and equipment.
- The direction of state and local law enforcement officers, including the National Guard.
- Prescription of evacuation routes, transportation modes, and destinations.
- Control of ingress to and egress from the disaster area.
- The ability to order, direct, compel, or recommend an evacuation.
- Municipalities, counties, and parishes are given responsibilities to protect the health and safety of their citizens, including the authority to order an evacuation of their jurisdiction and to provide first responders.

### Evacuation at National Level

Country evacuation planning guidelines, according to the International Association of Oil & Gas Producers includes:

1. The establishment of a Crisis Command Center
2. Conduction of evacuation by a dedicated Crisis Management Team (CMT). CMT responsibilities include:
  - Safety and welfare of all personnel on duty
  - Minimization of impact on assets and property
  - Maintaining life continuity as much as possible
  - Planning and management of the evacuation
3. Identification and preparation of local staff in advance in order for the crew to go through proper training
4. Allocation of authorities to activate the evacuation plan with the country senior manager
5. Development of a staged security assessment process that will assist and facilitate in the preparation
6. Establishment of a reliable communication system for the evacuation team
7. Preparation of phased evacuation, setting the evacuation priority
8. Higher-risk/non-essential people leave first, consideration should be given to medical/health issues
9. First-available seating should be utilized, regardless of class of travel
10. Shelter in place – advise all personnel expatriates to initially stay within their lodgings
11. Define assembly points and staging areas
12. Passports/Tickets/Essential Items: create a list and set a hard limit about the size of the luggage available for each person
13. Medical first aid, tracking of missing personnel
14. Definition of a strategy for dealing with staff who refuse to leave the danger zone
15. Reception arrangements prior to actual evacuation





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# READI

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